3rd Electric Road Systems Conference 2019
Frankfurt am Main, Germany, 7th to 8th of May 2019

A techno-economic comparison of battery swap and electric road systems for heavy road transport. A German case study.

Daniel Speth[1*], Simon Árpád Funke[1]

[1]*Fraunhofer Institute for Systems and Innovation Research ISI, 76139 Karlsruhe, Germany*

* *daniel.speth@isi.fraunhofer.de (corresponding author)*

Summary

While electric vehicles are a promising solution to decarbonize passenger cars, the decarbonisation pathway for heavy road transport remains vague. Among other solutions, such as overhead lines or hydrogen, also battery swap systems might be interesting for use cases in the heavy road transport with only short idling periods that do not allow for a battery charge. Here, we techno-economically compare battery swap and electric road systems for a specific use case along the route Berlin-Peine, Germany. From a TCO-perspective both alternatives, battery swap stations and overhead catenary vehicles, seem to be an option to electrify heavy-duty road transport. While catenary vehicles can be cheaper in the long term, battery swap stations are built up comparatively easily with less financial risk.

1 Introduction

To reach ambitious greenhouse gas mitigation targets, a deep decarbonisation of the transport sector is necessary. While current development mainly focuses on passenger cars, for the heavy road transport no clear solution exists. However, the decarbonisation of heavy duty vehicles (HDV) is all the more important due to a high share of transport emissions - in Germany, about one third of CO_2 emissions from road transport are attributable to HDV - as well as due to still increasing transport volumes which lead to an increase in CO_2 emissions of 20 % in road transport in Germany since 1995 [8]. High annual vehicle kilometres travelled (in Germany ~75,000 km/a to 115,000 km/a for HDV with a gross vehicle weight above 12t, c.f. [3]) are advantageous in order to compensate high purchase costs of alternative drivetrains by lower operating costs. In contrast, high vehicle ranges in combination with a suitable charging infrastructure network are needed which is challenging for alternative vehicles. Due to a lack of technical maturity and/or infrastructure, the test possibilities of trucks with alternative propulsion systems (hydrogen, overhead contact line, synthetic fuels) are limited. In addition, since pure battery electric HDV are less flexible due to necessary charging times, in the project "RouteCharge", a battery HDV with a battery swap system is assembled and tested alongside a specific route that will be equipped with three battery swap stations (details see Section 2). However, battery swap systems are cost-intensive due the need for extra batteries. The question rises if there might be niche applications in heavy road transport where battery swap systems may play a role or if other alternative drivetrains might be techno-economically more attractive in the medium to long term.

1.1 Research Questions and scope of the study

This study aims at comparing possible battery electric solutions for the heavy road transport sector from a technical and economical perspective for the year 2030. Since operational requirements do not allow for longer charging stops (see next Section), our comparison focuses on battery swap vehicles (BSV) and catenary battery electric vehicles (CV). Accordingly, the research question of this study is

> *How do battery swap systems for HDV compare to catenary trucks with regard to technical feasibility and cost for regular use along the route Berlin-Peine?*

The exact operating conditions for the application are described in the next section.

2 Data

2.1 Case study Berlin-Peine: route specific data

The BSV will be operated along the route Berlin-Peine, as illustrated in Figure 1. The distance is 250 km with a battery swap station at both end points and in the middle. The maximum idle time during loading procedure is 20 min.

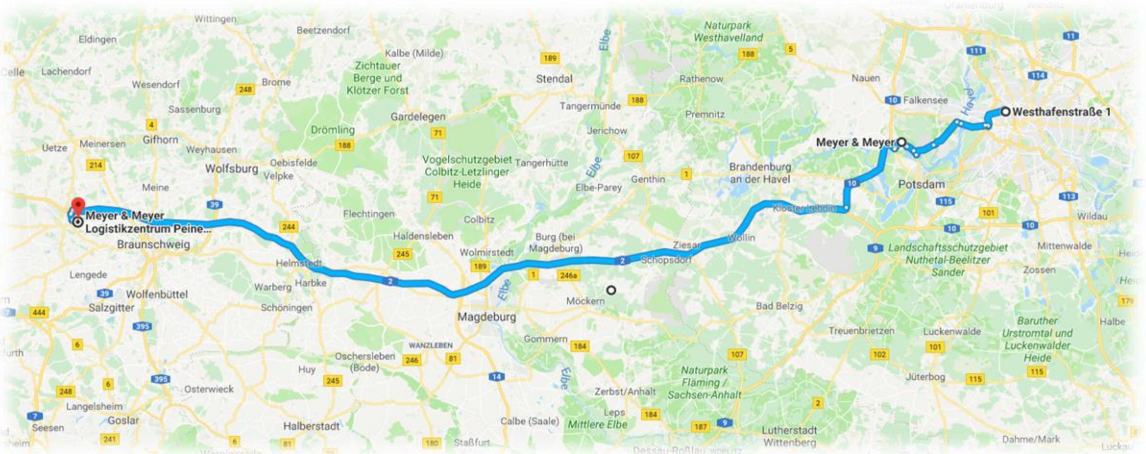

Figure 1: Course of the investigated route Berlin-Peine. Battery swap stations (to be) located at the two end points and in the middle of the route. Background source: Google Maps.

For the comparison, we assume the following different infrastructure scenarios:

1. BSV3: a BSV with all three swap stations as described above
2. CV40: a CV with catenary infrastructure reaching from Peine to Magdeburg (40% of route length).
3. CV80: a CV with catenary infrastructure reaching from Peine to Werder (80% of route length).

The scenario CV40 corresponds to the national catenary infrastructure expansion level 2 as described in [10] and comprises 40% of the route length from Peine to Magedburg. Accordingly, CV40 represents expansion level 3 and a route coverage of 80% from Peine to Werder.

In mid- to long-term perspective we investigate the service of seven vehicles driving this route daily.

2.2 Techno-economic parameters

The techno economic data for our analysis is summarized in the following three Tables. For technical and economic vehicle data see Table 1, general techno-economic data on battery, fuel and electricity, respectively is summarized in Table 2 and finally, techno-economic data on the respective infrastructure equipment can be found in Table 3. Despite a thorough literature analysis, techno-economic data on catenary and battery-swap electric HDV and their infrastructure are associated with uncertainties due to the long term perspective and a lack of broad literature.

Attribute	Abbr.	Unit	Diesel	BSV3	CV40	CV80	Source
Investment vehicle of drive train s without battery	I_S	EUR	105,485	77,590	87,590	87,590	[4,5,10]
Energy Demand for a vehicle of drive train s	e_s	kWh/km	2.38	1.42	1.51	1.51	[4]
Costs for O&M for a vehicle of drive train s	$c_{O\&M,s}$	EUR/km	0.1517[1]	0.126	0.107	0.107	[10]
Investment horizon	T	a	6	6	6	6	[4]
Vehicle kilometre travelled for a vehicle of drive trains s	VKT_s	km	120,000	120,000	120,000	120,000	[4]
Distance driven by battery	$d_{b,s}$	%		100	60	20	Route data
Max. distance driven by battery	d_{max}	km		125	300	100	Route data

Table 1: Vehicle parameters in 2030

Attribute (w/o VAT)	Abbr.	Unit	Value 2030	Source
Battery price	I_b	EUR/kWh	186	[7]
Cycle life	CL	Full cycles	5,000	[9]
Battery C-rate			2	Project data
Diesel price	$c_{e,Diesel}$	EUR/kWh	1.53	[6,10]
Electricity price industrial	$c_{e,Electricity}$	EUR/kWh	0.16	[1]

Table 2: General parameters in 2030

1 Including AdBlue

Attribute	Abbr.	Unit	BSV		CV40	CV80	Source
			simultaneous arrival	arrival distributed over the day			
Specific investment		EUR/km			1,696,750	1,696,750	[10]
Total length		km			2,000	3,000	[10]
Total investment	I_{BS}, I_{CV}	kEUR	1,650[2]	693[2]	3,393,500	5,090,250	
Operating cost	$c_{opex,BS}$, $c_{opex,CV}$	EUR/a	16,500[2]	6,930[2]	67,870,000	101,805,000	Project data, [10]
Investment horizon	T	a	30	30	30	30	[10]
Number of trucks in system	BSV, CV	#/a	7	7	61,875	62,022	[10]
Vehicle kilometres travelled by one vehicle on infrastructure	$VKT_{avg@s}$	km/a	VKT_s	VKT_s	61,900	69,400	[10]
Number of batteries per vehicle	#battery	#	2.3	1.4	1	1	Project data
Max. power at one swap station		kW	1,065[3]	52 / 104[3]			Project data, [10]

Table 3: Infrastructure parameters in 2030

The investment for BS accounts for three battery swap stations serving seven vehicles. The investment in the BSS highly depends on the arrival rate of the HDV especially since a higher arrival rate makes a higher grid connection power necessary. Accordingly, Table 3 shows two extreme use cases: one where all HDV arrive simultaneously at the BSS and one where the HDV arrive distributed over the day. The cost for the BSS are unknown, since no empirical values exist. We therefore base our assumptions on the BSS on cost assumptions of EV charging infrastructure. Accordingly, we assume the investment of a BSS to consist of a fixed part (170,000 €) for grid connection, storage and battery swap equipment and a variable part as a function of the necessary grid connection power (300 €/kW). The electrical power is set as function of the HDV arrival rate by aiming at minimizing the number of batteries in the whole system in compliance with a maximum C-rate of 2.

The VKT in Table 3 refer to a typical vehicle that uses the infrastructure. Since the BSV are used by one owner exclusively, the VKT in Table 3 are identical with the VKT_s of a BSV in Table 1.

2 Investment and cost account for three BS and serve seven vehicles.

3 If HDV arrive distributed over the day, the BSS in the middle requires twice the connection power of the other two since it has to serve both directions. If all HDV arrive simultaneously, all BSS have the same power.

3 Methodology

The approach of this study comprises two steps, namely the technical battery design ("how much range is required?") of the BSV and the CV and second, the economic analysis of both, compared to a diesel truck.

If an abbreviation is not explained directly, the meaning can be found at chapter 2.2.

The battery must be dimensioned in such a way that the maximum distance d_{max} between two charging options (catenary overhead line or battery swap) can be driven fully electrically. Accordingly, the battery capacity κ is calculated for every infrastructure (see Section 2) and vehicle option s individually, as:

$$\kappa_s = \frac{1}{0.8} * d_{max} * e_s * b \tag{1}$$

We use the factor 1/0.8 to account for the usable battery capacity at its end of life. e_s represents the specific average energy demand [kWh/km]. Additionally there is a buffer $b = 1.1$ considered, e.g. for additional heating demand during winter season. We assume the battery being modular in 25 kWh steps.

For heavy-duty vehicles, cost are the most important decision-making basis [3], for logistics especially per-kilometre cost [10]. Accordingly, we compare the two alternatives based on per-kilometre total cost of ownership (TCO) that consist of capital expenditures for the vehicle and the battery as well as operating expenditures. In the CV-case, each vehicle has one battery depreciated within the investment horizon of the vehicle ($T_{bat,CV} = 6$). In the BS-case, the batteries do not belong to one specific heavy-duty vehicle but can be assumed to be a part of the battery swap infrastructure. As described above the number of batteries in the system depends on the vehicle arrival rate at the BSS (and the maximum charging rate of the batteries). For the given scenarios of seven vehicles, driving either equally distributed during the course of the day (205 minutes tact) or arriving simultaneously as platoon (10 minutes tact), 10 or 16 batteries are necessary. Since batteries might last longer if more batteries are used, the investment horizon of the batteries $T_{bat,BS}$ depends on the specific use case and is calculated as

$$T_{bat,BS} = Min(\frac{\kappa_{BSV} * CL * \#battery}{VKT_{BSV} * \#BSV * e_{BSV}}, 8) \tag{2}$$

We assume the calendar life of the battery - and thus $T_{bat,BS}$ - to be not higher as eight years (based on battery warranty of current BEV).

The capital expenditures of one vehicle (excluding the battery) are calculated as

$$a^s_{capex} = \frac{I_s * (1+i)^T * i}{(1+i)^T - 1} \tag{3}$$

The capital expenditures of the battery are calculated accordingly, but taking the different number of batteries and their different lifetimes for the different scenarios into account.

The operating expenditures of the vehicle - including km-specific charging infrastructure cost $c_{i,s}$ - are defined as

$$a^s_{opex} = VKT_s * ((c_{e,s} * e_s) + c_{i,s} + c_{O\&M,s}) \tag{4}$$

Aspects like heavy duty vehicle toll or others are assumed to be equal between different drive train technologies and are thus neglected.

While BS-infrastructure might be a private investment, CV-infrastructure is capital intensive and therefore must be used by different companies and installed by a third party. Therefore, we use two different approaches to calculate the costs for infrastructure usage. For the CV-infrastructure we take a nationwide perspective and allocate the total costs of the nationwide infrastructure to all kilometers driven at the CV-infrastructure ($VKT_{avg@CI} * \#CV$).

$$c_{i,CV} = \frac{\frac{I_{CV} * (1+i)^T * i}{(1+i)^T - 1} + c_{opex,CV}}{VKT_{avg@CI} * \#CV} \quad (5)$$

The costs for battery swap infrastructure are calculated as:

$$c_{i,BS} = \frac{\frac{I_{BS} * (1+i)^T * i}{(1+i)^T - 1} + c_{opex,BS}}{VKT_s * \#BSV} \quad (6)$$

Operating cost for the infrastructure are assumed as fix (c.f. Table 3).

4 Results

4.1 Technological comparison

From a technical perspective, we focus on the battery system of the vehicles. The results are summarized in Table 4. A battery density of 250 Wh/kg seems possible in 2030 [2,4]. Although such batteries are technically feasible, a loss of freight loss is likely [2,10]. However, freight loss is only relevant for the CV40 and only if payload is always fully exhausted. For the sake of simplicity, freight losses are neglected.

Attribute	Abbr.	Unit	BSV3	CV40	CV80
Battery capacity for a vehicle of drive trains s	κ_s	kWh	250	625	225
Battery weight 2030	w	kg	1.000	2.500	900
Range for a vehicle of drive train s	R_s	km	141	338	113
Max. distance driven by battery	d_{max}	km	125	300	100

Table 4: Battery configuration for different drive trains

4.2 Cost comparison

As shown in Figure 2, the battery swap vehicle is a competitive alternative for HDV, but its economic feasibility is highly dependent on infrastructure utilisation.

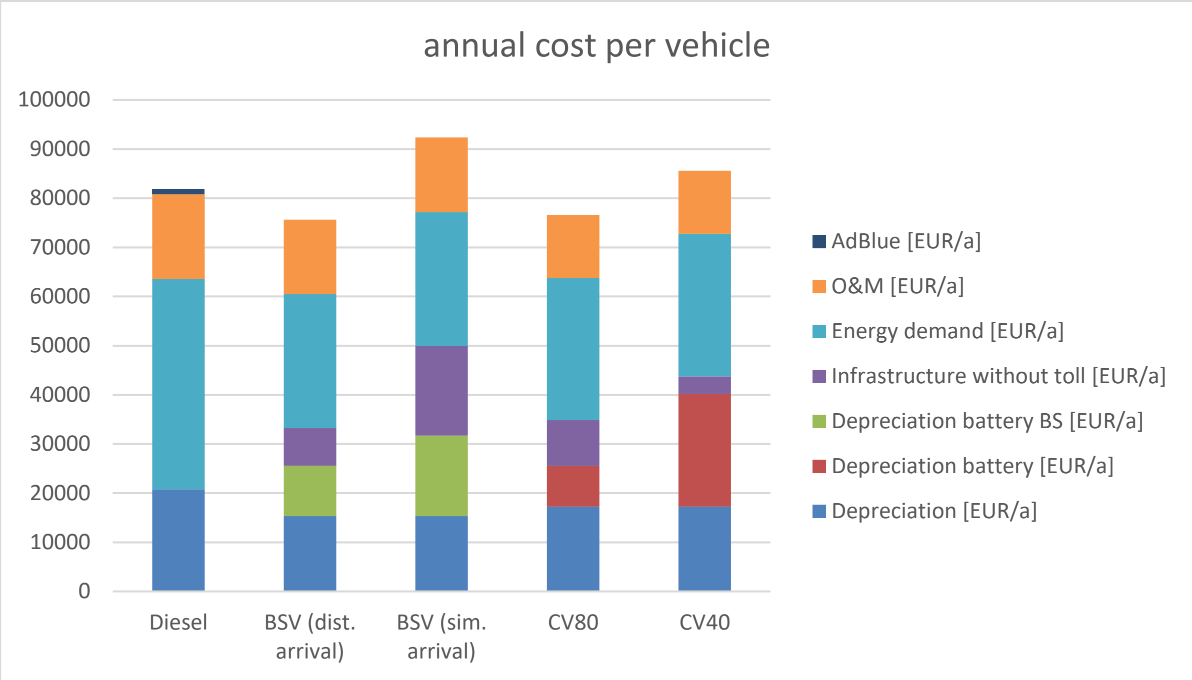

Figure 2: Annual costs per vehicle (10 minutes tact)

The previous chapter shows that both technologies, BSV and CV, can be an appropriate solution in order to electrify heavy-duty road transport. Due to its private ownership, the BSV concepts presents a good solution whenever a catenary infrastructure is not reachable. Even a combination of both technologies seems feasible.

5 Discussion

At first glance, BSV seems to be an alternative to electrify heavy-duty vehicles from an economic point of view. However, there are relevant aspects for further investigation. On the one hand, dimensions beside the economic point of view should be checked, e.g. ecological aspects. On the other hand, we have to gain a deeper understanding of BSV. Since there is no BSV in operation today, almost all data are literature-based. Test data from the demonstration project in Berlin-Peine will provide a deeper understanding. Especially the configuration of the battery swap station should be further investigated since the estimates contain uncertainties. For example in the current paper, we did no optimization concerning the relation between additional batteries and higher loads but minimized the number of batteries. Further investigation should focus on this aspect. Finally, the impact of the different infrastructure on the energy generation and the electric grid have to be further analyzed. Especially due to the increasing share of renewable energy generation, inflexible loads, such as catenary trucks, will play an important role. We will address these questions in the pilot project "eWayBW", in which infrastructure for catenary trucks will be built-up and the vehicle will be tested.

6 References

[1] Auf der Maur, A.; Rommerskrichen, S.; Strassburg, S. (2015): *Aktualisierung des Referenzszenarios für die Einsparpotentiale der Treibhausgas-Emissionen und des Endenergieverbrauchs im Verkehr für die Zeithorizonte 2020 und 2050 – vertraulich. Aktualisierung der Prognoseergebnisse sowie Abschätzung und Bewertung politischer Maßnahmen*. Client: Federal Ministry for Transport and Digital Infrastructure (BMVI). Prognos AG. Basel, Switzerland.

[2] Earl, T.; Mathieu, L; Cornelis, S.; Kenny, S.; Ambel, C., Nix, J.: *Analysis of long haul battery electric trucks in EU. Marketplace and technology, economic, environmental, and policy perspectives*. Transportenvironment. 8th Commercial Vehicle Workshop. Graz. Switzerland.

[3] Gnann, T., Kühn, A., Plötz, P., & Wietschel, M. (2017). *How to decarbonise heavy road transport*. eceee Summer Study 2017.

[4] Kühnel, S.; Hacker, F.; Görz, W. (2018): *Oberleitungs-Lkw im Kontext weiterer Antriebs- und Energieversorgungsoptionen für den straßengüterverkehr. Erster Teilbericht des Forschungsvorhabens "StratON - Bewertung und Einführungsstrategien für oberleitungsgebundene schwere Nutzfahrzeuge"*. Client: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. Öko-Institut e.V.. Berlin.

[5] Mareev, I.; Sauer, D. (2018): *Energy consumption and Life Cycle Cost of Overhead Catenary Heavy-Duty Trucks for Long-Haul Transportation*. Energies 11 (12).

[6] Schade, W.; Wietschel, M. (2016): "*Energiepreise für ein Referenzszenario der MKS*" (ARBEITSPAPIER zum Projekt Unterstützung des BMVI bei der Weiterentwicklung der Mobilitäts- und Kraftstoffstrategie).

[7] Thielmann, A.; Sauer, A.; Wietschel, M. (2015): *Produkt-Roadmap Energiespeicher für die Elektromobilität 2030*. Fraunhofer ISI. Karlsruhe. Germany.

[8] Umweltbundesamt (2018): Emissionen des Verkehrs. https://www.umweltbundesamt.de/daten/verkehr/emissionen-des-verkehrs#textpart-1

[9] Wietschel M; Kühn, A; Gnann T.; Speth, D.; Balz, W.; Frik, H.; Stütz, S.; Scheller, M. (2016): *Hybrid-Oberleitungs-Lkw: Potenziale zur Elektrifizierung des schweren Güterverkehrs. Fachworkshop 1. März 2016, Bundesministerium für Verkehr und digitale Infrastruktur Workshop im Rahmen der Wissenschaftliche Beratung des BMVI zur Mobilitäts-und Kraftstoffstrategie*. Studiennehmer: Fraunhofer ISI (Koordination), Fraunhofer IML, PTV Group, Technische Universität Hamburg-Harburg (TUHH), M-FIVE. FhG ISI: Dortmund, Hamburg, Karlsruhe, Germany.

[10] Wietschel, M.; Gnann, T.; Kühn, A.; Plötz, P.; Moll, C.; Speth, D.; Stütz, S.; Schellert, M.; Rüdiger, D.; Balz, W.; Frik, W.; Waßmuth, V.; Paufler-Mann, D.; Rödl, A.; Schade, W.; Mader, S. (2017): *Machbarkeitsstudie zur Ermittlung der Potentiale des Hybrid-Oberleitungs-Lkw. Studie im Rahmen der wissenschaftlichen Beratung des BMVI zur Mobilitäts- und Kraftstoffstrategie der Bundesregierung*. Fraunhofer ISI, Karlsruhe, Fraunhofer IML, Dortmund, PTV Transport Consult GmbH, Stuttgart, Karlsruhe, TU Hamburg-Harburg, Hamburg, M-Five, Karlsruhe, Germany.

7 Authors

Daniel Speth is a Scientist at the Competence Center Energy Technology and Energy Systems at the Fraunhofer Institute for Systems and Innovation research in Karlsruhe, Germany. Areas of work are the economic and technical implications of changes in heavy-duty vehicles road transport with a special focus on catenary vehicles.

Simon Árpád Funke is a Senior Scientist at the Competence Center Energy Technology and Energy Systems at the Fraunhofer Institute for Systems and Innovations research in Karlsruhe, Germany. He received his PhD from University of Kassel, Germany, for his research on the range of battery electric vehicles. Areas of work are the technology and usage patterns of alternative drive systems.