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

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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 CO₂ emissions from road transport are attributable to HDV - as well as due to still increasing transport volumes which lead to an increase in CO₂ 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 Magdeburg. Accordingly, CV40 represents expansion level 3 and a route coverage of 80% from Peine to Werder.

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

Table 1: Vehicle parameters in 2030

<table>
<thead>
<tr>
<th>Attribute (w/o VAT)</th>
<th>Abbr.</th>
<th>Unit</th>
<th>Value 2030</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery price</td>
<td>$I_b$</td>
<td>EUR/kWh</td>
<td>186</td>
<td>[7]</td>
</tr>
<tr>
<td>Battery life time</td>
<td>$BLT$</td>
<td>Full cycles</td>
<td>5,000</td>
<td>[9]</td>
</tr>
<tr>
<td>Diesel price</td>
<td>$c_{e,Diesel}$</td>
<td>EUR/kWh</td>
<td>1.53</td>
<td>[6,10]</td>
</tr>
<tr>
<td>Electricity price commercial</td>
<td>$c_{e,Electricity}$</td>
<td>EUR/kWh</td>
<td>0.22</td>
<td>[1]</td>
</tr>
</tbody>
</table>

Table 2: General parameters in 2030

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1 Including AdBlue
### Table 3: Infrastructure parameters in 2030

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Abbr.</th>
<th>Unit</th>
<th>BS</th>
<th>CV40</th>
<th>CV80</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific investment</td>
<td></td>
<td>EUR/km</td>
<td>1,636,750</td>
<td>1,636,750</td>
<td>[10]</td>
<td></td>
</tr>
<tr>
<td>Total length</td>
<td></td>
<td>km</td>
<td>2,000</td>
<td>4,000</td>
<td>[10]</td>
<td></td>
</tr>
<tr>
<td>Total investment</td>
<td>$I_{BS}, I_{CV}$</td>
<td>kEUR</td>
<td>200²</td>
<td>3,273,500</td>
<td>6,547,000</td>
<td>Project data</td>
</tr>
<tr>
<td>Operating cost</td>
<td>$c_{opex,BS}, c_{opex,CV}$</td>
<td>EUR/a</td>
<td>200¹</td>
<td>65,470,000</td>
<td>130,940,000</td>
<td>Project data, [10]</td>
</tr>
<tr>
<td>Investment horizon</td>
<td></td>
<td>a</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>[10]</td>
</tr>
<tr>
<td>Number of trucks in system</td>
<td>$BSV, CV$</td>
<td>#/a</td>
<td>1</td>
<td>66,000</td>
<td>[10]</td>
<td></td>
</tr>
<tr>
<td>Vehicle kilometres travelled by one vehicle</td>
<td>$VKT_S, VKT_{avg}$</td>
<td>km/a</td>
<td>120,000</td>
<td>74,563</td>
<td>[10]</td>
<td></td>
</tr>
</tbody>
</table>

While the BS infrastructure parameters describe one battery swap station, the data of the CV account for the whole system installed. 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 of a BSV in Table 1.

In the full paper we will provide empirical data on route specific driving energy and charge efficiency. Finally, we expect to have more detailed data on the battery swap process.

### 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.

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 $\kappa$ is calculated for every infrastructure (see Section 2) and vehicle option $s$ individually, as:

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

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 BS-case, the battery does not belong to one specific heavy-duty vehicle. To ensure steady service each car and each BS-station has to be equipped with one battery. Accordingly, the cost of capital for one battery are added to capital expenditures for the vehicle and the BS-station. The actual use of the battery

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² Investment and cost are per battery swap station and split over BSV = 10 vehicles.
is modelled as part of the operating expenditures of the truck. In order to provide stringency, we use the same method for the catenary truck. The capital expenditures of the vehicle are calculated as

\[
a^T_{\text{cap ex}} = \frac{I_s (1 + i)^T}{(1 + i)^T - 1} + i \cdot I_b \cdot \kappa_s
\]  

(2)

The operating expenditures of the vehicle - including km-specific charging infrastructure cost \( c_{LS} \) - are defined as

\[
a^T_{\text{op ex}} = V K T_s \cdot ((c_{e,s} \cdot e_s) + (I_b \cdot \kappa_s \cdot \frac{e_s \cdot d_{b,s}}{\kappa_s \cdot BLT}) + c_{I,s} + c_{O&M,s})
\]  

(3)

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, the costs are allocated to the kilometers travelled in the CV-system.

\[
c_{L_{CV}} = \frac{L_{CV} \cdot (1 + i)^T}{(1 + i)^T - 1} + c_{\text{op ex, CV}}
\]  

(4)

The costs for infrastructure of BS-vehicles for each BS-station including the interest rate for one battery per station are calculated as described in the following formula.

\[
c_{LBS} = \frac{3 \cdot (L_{BS} \cdot (1 + i)^T}{(1 + i)^T - 1} + c_{\text{op ex, BS}} + i \cdot I_b \cdot \kappa_s}
\]  

(5)

Operating costs are assumed as fix (c.f. Table 3).

In the full paper, we will give some more details of our methods.

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]. In the full paper, we will strengthen the battery analysis concerning freight loss and necessary C-Rates. Additionally, we will debate whether the assumed infrastructure for CV is properly dimensioned.
### Attribute Abbr. Unit BSV CV40 CV80

<table>
<thead>
<tr>
<th>Battery capacity for a vehicle of drive trains s</th>
<th>$\kappa_s$</th>
<th>kWh</th>
<th>250</th>
<th>625</th>
<th>225</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery weight</td>
<td>$w$</td>
<td>kg</td>
<td>1.000</td>
<td>2.500</td>
<td>900</td>
</tr>
<tr>
<td>Range for a vehicle of drive train s</td>
<td>$R_s$</td>
<td>km</td>
<td>141</td>
<td>338</td>
<td>113</td>
</tr>
<tr>
<td>Max. distance driven by battery</td>
<td>$d_{max}$</td>
<td>km</td>
<td>125</td>
<td>300</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 4: Battery configuration for different drive trains

#### 4.2 Cost comparison

For the given scenario, the different drive trains lead to quite similar costs, as shown in Figure 2. Although the Diesel engine is approximately 1,000 EUR cheaper than the CV80 and 6,000 EUR cheaper than the BSV and the CV40, both technologies seem to be a possibility to realize electric driven heavy-duty road transport.

![Annual costs per vehicle](image)

Figure 2: Annual costs per vehicle

#### 4.3 Synthesis

The previous chapter shows that both technologies, BSV and CV, can be an appropriate solution in order to electrify heavy-duty road transport. A highly used and well-expanded catenary infrastructure (CV80) seems to be cheaper for an individual heavy-duty vehicle. 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. In the full paper, we will present the data (technical and economic) from the RouteCharge project Berlin-Peine in order to recheck the literature-based calculation.
5 Discussion
In the full paper we will provide a short critical discussion of our findings.

6 References


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.

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