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ERS – Modelling a cost-efficient rollout Scenario for Germany

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Abstract

The introduction of Electric Road Systems (ERS), such as overhead catenary trucks (OC trucks), faces the challenge of high initial infrastructure costs. This bears the risk of a financial “valley of death” until there are sufficient revenues from system operation (see [1]). By using a smart selection and prioritization of infrastructure installation, this risk can be reduced with suitable policy measures. Thus, we identify suitable highways for OC system introduction using a linear optimisation model. The objective function of the model expresses the total cost minimum including the TCO of trucks and infrastructure cost. The model also considers constraints like the maximum annual extension rate of the catenary network.

1 Research Question

Electric road systems can decarbonize road transport and simultaneously contribute significantly to the political goal of energy conservation. On the other hand, necessary infrastructural investments are considerable and need to be justified by proving their cost-effectiveness. Thus, governments seek to select road stretches for infrastructure installation that are particularly suitable to leverage a ramp-up of the ERS vehicle market. This work introduces a novel approach to identify a sequence of suitable road stretches for electrification based on a linear optimization. The abstract has a focus on the description of the approach, which constitutes the (intermediary) result. For the conference presentation, we will enhance this with some exemplary results from the calculation runs.

2 Methodology

The basic idea is to first identify routes on which vehicles might have the biggest financial advantage (in terms of total cost of ownership – TCO) from the technology shift. On this basis, we select motorway sections with high utilisation by these vehicles. The vehicles with their respective TCO and the motorway sections with their infrastructure status constitute the input for a linear optimization problem.

Formally, linear programming is a technique for the optimization of an objective function, subject to equality and inequality constraints. This means a mathematical formulation of the system parameter that shall be maximised or minimized, while simultaneously maintaining certain boundary conditions. The coefficients of the objective function and constraints are in the presented model mainly given by the traffic flow and the OC system’s costs (vehicles and infrastructure). We chose the following steps in order to estimate these coefficients needed to formulate the linear optimization problem:

- The basis of the analysis is the transport model “PTV Validate”. The model covers the whole road transportation in Germany whereby the transport volume is defined by the number of daily trips between locations. The number of the relevant trips is reduced by considering only trips with a high potential for shifting to the OC technology. This means, we only take into account trips conducted by trucks with a minimum weight of 26 t. Furthermore, we consider only trips with a high mileage on highways and excluding transit traffic. Moreover, only the transport of certain goods is considered which have been selected by general suitability criteria for ERS, e.g. the likelihood of shuttle operation. The methodology of this preliminary step is documented in [2] and has been presented at last year's conference [3]. The result of this first step is a matrix of principally ERS suitable origin-destination pairs with the corresponding vehicle counts. These results are illustrated in Figure 1.

Figure 1: Traffic volumes due to suitable trips for OC semi-trucks on the German road network for the pilot phase (~2020)

- The second step creates a link between the trips identified in step 1 and the potential OC infrastructure. Therefore, we calculate for each trip the traversed highway sections and the off-highway mileage by means of a routing algorithm. By considering the energy consumption on the sections as well as the variable and fixed costs of the trucks used on the trips, it is possible to decide whether an OC truck is more cost efficient than a conventional truck. These data constitute the input for the optimization problem (Figure 2).

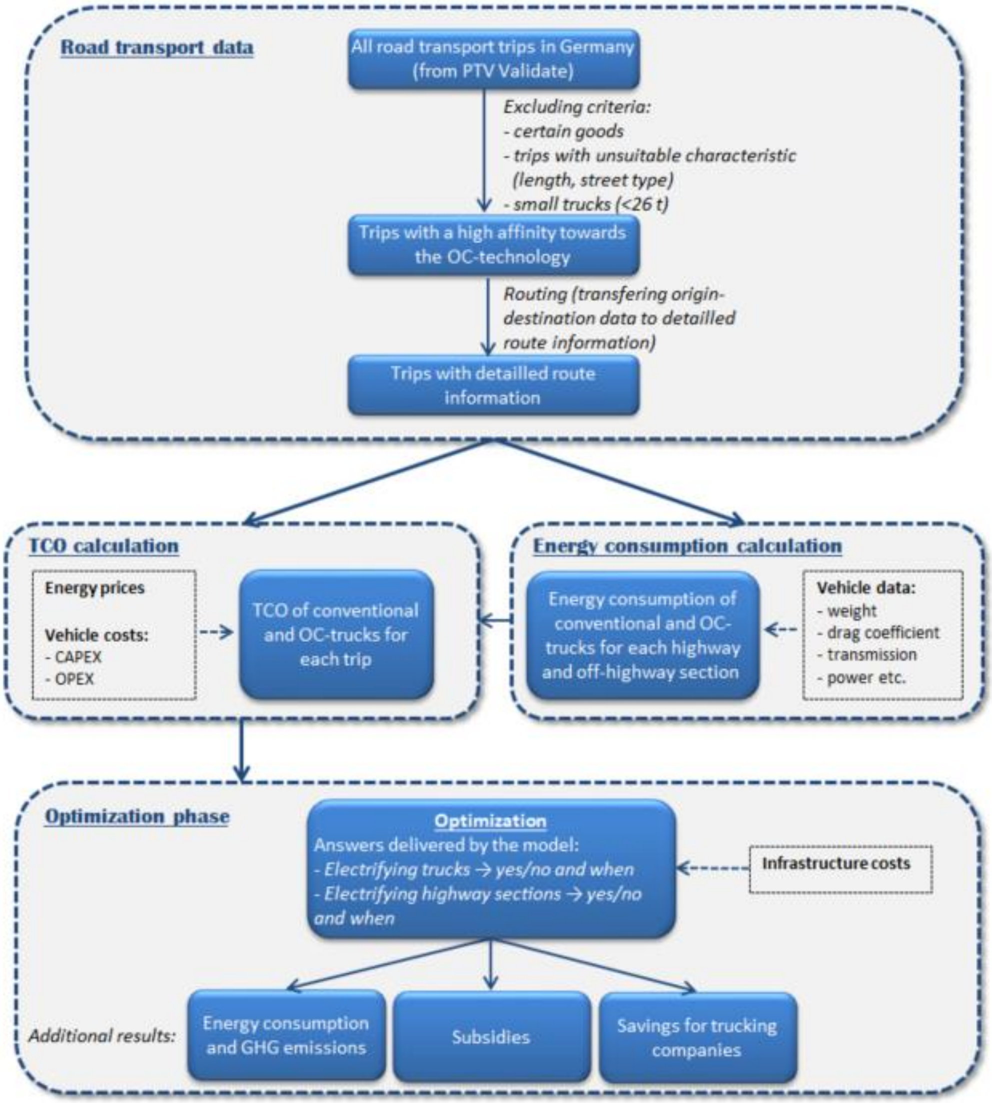

Figure 2: Methodology of calculating a cost-efficient roll out scenario for ERS using linear programming

3 Results

Based on the input data derived above a linear optimization is used to find a sequence of infrastructure deployment within the considered timeframe which yields minimum overall system costs (= sum of trucking company costs and infrastructure costs). If the electrification of a specific highway section costs less than the savings resulting from the shift to OC-technology of trucks operating on this section, this section is selected for electrification. The model is built to encompass defined years e.g. infrastructure development until 2030 or more. This means that segments where electrification is not viable by itself might nevertheless be electrified if this pays off in the future when the whole infrastructure network is considered.

The objective function is the minimisation of the total costs, including the fixed and variable costs of the trucking firms and the infrastructural costs for construction and maintenance. All costs are given in equivalent annual cost. Thus, investment costs are allocated to the technology's life span. The costs and savings of the vehicles are defined as the cost difference between an OC truck and a conventional truck on the given route. The objective function is thus given by:

$$\min\{\sum_{i,t} v_{i,t} \cdot \mathrm{n}_{\mathrm{i,t}} \cdot \left(\mathrm{k}_{\mathrm{i,t}}^{\mathrm{veh,fix}} + \mathrm{k}_{\mathrm{i,t}}^{\mathrm{veh,off-highway}}\right) \rightarrow \text{differential fixed vehicle and off highway cost}$$

$$+\sum_{i,j,t} e_{i,j,t} \cdot \mathrm{n_{i,t}} \cdot \mathrm{k^{veh,var,el}_{i,j,t}}$$ → differential variable cost on electric highway

$$+\sum_{i,j,t} d_{i,j,t} \cdot \mathrm{n_{i,t}} \cdot \mathrm{k^{veh,var,d}_{i,j,t}}$$ → differential variable cost on not electrified highway

$$+\sum_{j,t} s_{j,t} \cdot \mathrm{k^{inf}_{j,t}} \}$$ → variable and fixed infrastructure cost

The italic letters symbolize the result variables that are calculated in the model. The constants are calculated prior to the optimization for each vehicle (k^{veh}) or road segment (k^{inf}) respectively based on sub-models for infrastructural costs and the vehicle's TCO. The following table indicates the used variables, indices and constants.

Variables

$v_{i,t}$	Indicates if the trucks on the trip *i* in the year *t* are OC-trucks (0-conventional, 1-OC)
$e_{i,j,t}$	Indicates if OC-trucks on the trip *i* and section *j* in the year *t* are driven electrically (0-no, 1-yes)
$d_{i,j,t}$	Indicates if OC-trucks on the trip *i* and section *j* in the year *t* are driven with the Diesel engine (0-no, 1-yes)
$s_{j,t}$	Indicates if the highway section *j* in the year *t* is electrified (0-no, 1-yes)

Constants

$\mathrm{n}_{i,t}$	Number of trucks serving on the trip *i* in the year *t*
$\mathrm{k^{veh,fix}_{i,t}}$	Annual fixed vehicle costs on the trip *i* in the year *t*
$\mathrm{k^{veh,off-highway}_{i,t}}$	Annual operational vehicle costs on the trip *i* in the year *t* off the highway sections
$\mathrm{k^{veh,var,el}_{i,j,t}}$	Annual operational vehicle costs on the trip *i* and the section *j* in the year *t*, if the trip *i* and section *j* are electrified
$\mathrm{k^{veh,var,d}_{i,j,t}}$	Annual operational vehicle costs on the trip *i* and the section *j* in the year *t*, if the trip *i* is electrified and the section *j* is not electrified
$\mathrm{k^{inf}_{i,t}}$	Equivalent annual cost of infrastructure of the section *j* in the year *t*

The results of the optimization can help to answer e.g. the following questions:

- Which trips should be shifted to the OC-technology from a cost perspective and when?
- Which highway sections should be electrified from a cost perspective and when?
- How much electricity is needed and where does the demand occur?

Several boundary conditions are applied to the model. Some of these constitute an inherent part of the problem definition:

$$e_{i,j,t} + d_{i,j,t} = \mathrm{f_{i,j,t}} \cdot v_{i,t} \forall\, i,j,t$$

→ Either Diesel or electric drive if OC truck is chosen (f ∈ [0,1], represents if trip *i* is via section *j*)

$$v_{i,t} \leq 1 \;\forall\, i,t$$

→ 0-conventional truck is used on trip *i*, 1-OC truck is used

$$e_{i,j,t} \leq s_{j,t} \;\forall\, i,j,t$$

→ Electric drive only on electrified highway sections

$$s_{j,t} \leq s_{j,t+1} \;\forall\, j,t$$

→ Constructed grid is maintained

$$0 \leq v_{i,t}, e_{i,j,t}, d_{i,j,t}, s_{j,t} \leq 1 \;\forall\, i,j,t$$

→ All variables are binary.

Additional restrictions may be defined by the political framework. For example, a cap for CO_2 emissions for heavy-duty-vehicles can be easily integrated into the model as follows:

$$\sum_{i,j} v_{i,t} \cdot \mathrm{GHG}_{\mathrm{i,t}}^{\text{off highway}} + e_{i,j,t} \cdot \mathrm{GHG}_{\mathrm{i,j,t}}^{\text{electric drive}} + d_{i,j,t} \cdot \mathrm{e}_{\mathrm{i,j,t}}^{\text{Diesel drive}} \geq \mathrm{GHG\ target_t}\ \forall\, t$$

This makes it possible to develop a cost-optimal roll-out scenario to achieve a defined CO_2 cap. Also, feasibility considerations can be implemented by using constraints. For example, a maximum infrastructure deployment per year would yield the following restriction:

$$\sum_{j} (s_{j,t} - s_{j,t-1}) \cdot \mathrm{l_j} \leq \mathrm{MaxDepl_t}\ \forall\, t$$

→ l represents the length of the highway section j.

Furthermore, interpretation of the results can help to answer some more complex issues:

- The distribution of costs and advantages within the system. For example: Which routes will be most advantageous for the operators?
- The ability of operators to contribute to infrastructure funding (by assessing the TCO difference of the OC trucks compared to conventional trucks). This can be used to determine the payback period of the system.
- The effects of certain supporting policy schemes. For example, energy taxation, toll exemption and grants for vehicle purchase can be realized by adjustment of the input parameters in order to conduct sensitivity analyses.

Overall, the approach is very versatile and may be applied to a wide number of questions. The results can of course only be as good as the underlying data. Particularly regarding the traffic flows, it has to be noted that these are in turn a model output (from PTV Validate) and have some known limitations. However, it is principally possible to integrate additional data for the traffic flows (e.g. floating car data) which will be a part of future work.

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Julius Jöhrens studied physics and political science at the University of Jena. Since 2010 he has been working at ifeu in the Transport and Environment department. He manages various projects in the field of alternative drive technologies, electricity-generated fuels and energy efficiency in transport. His focus lies on the analysis and simulation of usage profiles in order to assess feasibility of electric drivetrains for passenger as well as commercial vehicles.

Hinrich Helms studied geography at the University of Heidelberg. Since 2002, he has been a research assistant and senior scientist of the "Transport and Environment" department at the ifeu. He has carried out and managed numerous research projects on environmental impacts of transport and suitable measures (climate protection, air pollution). The main focus is on work in the field of environmental implications of different drive technologies for electromobility. On the basis of the life-cycle assessment model "eLCAr", generic drive technologies are compared.

Other key areas include the assessment of the environmental impacts of transport systems.