35th International Electric Vehicle Symposium and Exhibition (EVS35)
Oslo, Norway, June 11-15, 2022

Green truck technologies wanted! A cost-optimised drive train portfolio for Germany

Florian Heining[1], Julius Jöhrens[1],
Michel Allekotte[1], Hinrich Helms[1]

[1]*ifeu – Institute for Energy and Environmental Research Heidelberg, Wilckensstr. 3, 69120 Heidelberg,*
florian.heining@ifeu.de

Summary

We compare the potential of various electric truck drive technologies in terms of total cost of ownership for the year 2030. For each technology we calculate the fleet-wide truck mileage where the alternative technology shows a cost advantage over diesel trucks ("economic potential"). Second, we determine the technology with the lowest cost for each mission profile, i.e. a cost-optimized technology mix for trucking in Germany in 2030. Battery electric trucks show the lowest cost for the major share of applications, while catenary trucks can be competitive on long routes. The identified economic potential for fuel cell trucks is only marginal.

Keywords: BEV (battery electric vehicle), cost, freight transport, fuel cell vehicle, truck

1 Introduction and research question

In the development of effective strategies to reduce greenhouse gas (GHG) emissions from the transport sector drastically, road freight transport is increasingly coming into focus. At just under 50 Mt CO2 per year, it is responsible for around one third of transport-related emissions in Germany (with an upward trend). In contrast to passenger transport, where battery electric cars are already gaining market acceptance with subsidies or are already competitive in some segments without subsidies [1], there is still a lack of market-ready technical solutions for road freight transport.

In this study, we compare the potential of various truck drive technologies for a profitable operation (> 1% cost advantage) compared to diesel trucks in terms of TCO[1] ("economic potential") for the reference year 2030. Based on expected technical and economic developments in drive technologies, we have identified the trips on which new drive technologies have a cost advantage over diesel trucks for the operators in 2030 and which of the available technologies is associated with the lowest total cost of ownership in each use case. We considered battery-electric trucks (BEV), fuel-cell electric trucks (FCEV) and power supply via overhead line ("eHighway" technology) for battery catenary trucks (OC-BEV) and diesel hybrid trucks (OC-HEV). BEV and OC-BEV were analysed with different battery ranges, given in kilometers (e.g. an OC-BEV100 would indicate an OC-BEV with

[1] Total cost of ownership

100 km range outside the overhead line network). The results of the study show profitable areas of application for the considered technologies in 2030, based on the currently foreseeable policy framework in Germany. However, they should not be misinterpreted as a market ramp-up scenario, since fleet turnover rates are not considered. They rather indicate the share of truck mileage of the respective technology in Germany with the lowest cost for truck operators, assuming the vehicle is purchased in 2030 and used for a typical period of time.

2 Data and methods

The total cost of ownership (TCO) for various drive technologies are determined at the level of individual mission profiles. The overall economic application potential for each technology in Germany by 2030 is derived by selecting the drive technology with lowest TCO for each mission profile and integrating over all mission profiles.

Data basis for the calculations are domestic truck trips from the Germany-wide traffic model PTV Validate, which was calibrated using official forecast data from the German government for the year 2030 [2]. The model provides 1,25 million origin-destination relations for 16 types of goods and three truck size classes. We further divided the size classes into five classes to account for typical truck sizes in Germany: 3.5-7.5 t, 7.5-12 t, 12-18 t, 18-26 t and more than 26 t gross vehicle weight. The data also contains geographical information on the specific routes of each trip.

Since the sequence of trips for individual vehicles cannot be determined from the model data, a typical mission profile for operation on a given transport relation is characterized on the basis of the annual or daily mileage of trucks for different distance classes. Annual and daily mileage are linked in the model by the assumption of 250 operating days per year. The annual mileage determines the share of a vehicle's fixed costs in the total costs. The average daily mileage is decisive for the required range of the vehicles. Typical annual mileages of trucks are available from official statistics in Germany for operation in different distance classes: local (<50km), regional (50km-150km) and long-haul (>150km) [3]. Using non-linear regression, a functional relationship between the relation length and the annual mileage is derived, assuming that the function is of type

$$annual\ mileage = a \cdot trip\ length^{b} + c \qquad (1)$$

With this method, we obtain relation-specific mean values for daily driving distance and annual mileage, shown in *Figure 1*. If the trip length alone exceeds the derived annual mileage, assuming 250 operating days, the resulting annual mileage is used instead of the derived function (1). The coefficients *a, b* and *c* are chosen in a way that the average annual mileage of each size class and the average annual mileage of each distance class show good agreement with official statistics. Although the derived functions do not represent the possible range of variation in real-world cases, they do form a solid basis for comparing the economic efficiency of different drive technologies for operation on different relations.

The vehicle prices of trucks with different drive technologies were determined on the basis of an extensive literature analysis (e.g. [4], [5], [6]) assuming economies of scale upon entry into the mass market for all considered technologies. The assumed energy prices and infrastructure charges are based on projections of the German "National Platform for the Future of Mobility" [7]. Some key assumptions are summarized in Table 1 and Table 2. Since we suppose a mass market for alternative drive systems in 2030, we assume that the current subsidies in Germany will have expired by then (no purchase rebates, no toll exemptions).

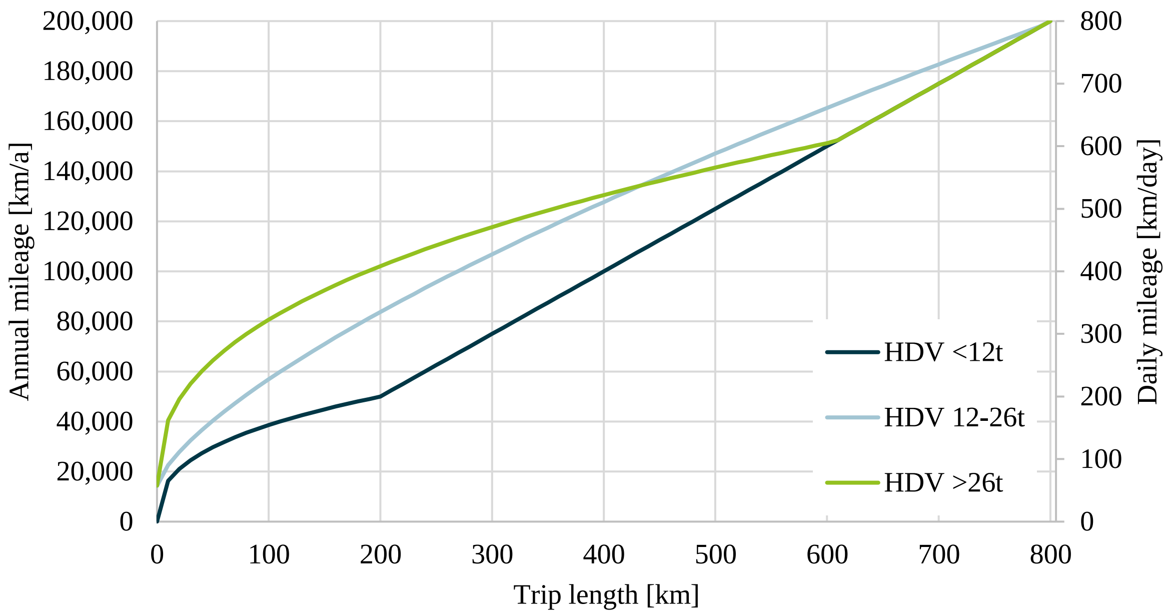

Figure 1: Derived relationship between trip length and annual mileage

Table 1: Assumptions for vehicle prices (2030) by vehicle class (gross weight)

	3.5-7.5 t	7.5-12 t	12-18 t	18-26 t	> 26 t
ICEV	41,300 €	56,000 €	66,300 €	89,500 €	103,000 €
BEV100[1]	31,400 € (+ 7,900 €)	44,700 € (+ 8,400 €)	59,300 € (+ 9,500 €)	77,000 € (+ 10,800 €)	90,200 € (+ 13,000 €)
FCEV	49,800 €	71,200 €	89,100 €	118,700 €	144,800 €
OC-BEV100[1]	/	/	74,700 € (+ 9,500 €)	92,300 € (+ 10.800 €)	106,100 € (+ 13,000 €)
OC-HEV	/	/	109,100 €	137,900 €	158,300 €

All prices in $€_{2020}$; [1] Prices for vehicles with 100 km range, in parentheses the assumed additional purchase price per additional 100 km range

Table 2: Assumptions for energy prices (2030)

Fuel/electricity retail prices			
Diesel fuel	Electricity	H_2 (electrolysis in Germany)	H_2 (import)
1.36 €/l (incl. 100 €/tCO2)	16.6 ct/kWh	9.45 €/kg	4.57 €/kg
Contribution for installation and operation of charging/refueling infrastructure			
Charging in depot	Charging at public fast chargers (750 kW)	Hydrogen	Electricity from overhead line
2.5 ct/kWh	1.1 ct/kWh	80.0 ct/kg	5.0 ct/kWh

All prices in $€_{2020}$

The electric driving range required for the operation of battery trucks on a specific route is determined mainly based on the daily vehicle mileage. However, the calculation also includes assumptions on breaks (mandatory resting time of 45 min after 4.5 hours of driving) during an operating day, in which the trucks can be charged at public infrastructure. Sufficient availability of such charging infrastructure [2] is assumed in the analysis. Furthermore, we made assumptions on charging availability at loading bays and loading time of the goods for 16 different groups of goods, based on expert input. It is assumed that vehicles start the day with a full battery that has been charged with a company charger overnight. At the end of each trip a loading/unloading stop is assumed, where, depending on the type of good, the battery can be charged during loading for further trips. For OC-BEV, a basic network of overhead lines of about 3,050 km total length on the German motorway network is assumed [8]. As a sensitivity, we also ran the calculations with a smaller network of 1,450 km (see Figure 2).

Figure 2: Assumed overhead line network for catenary trucks (light blue roads are part of the 3,050 km basic network)

A detailed description of all model assumptions, such as vehicle holding period, battery aging, charging behaviour etc. can be found in [9].

3 Results

3.1 Economic potential of each technology compared to diesel trucks

In a first step we calculated the economic potential for the application of different alternative drive technologies compared to diesel trucks separately for each technology for the reference year 2030. For BEV, we looked at three different cases:

[2] For public fast charging we assumed 500 kW, for overnight and loading bay charging 200 kW with a total efficiency of 86 % (losses in the charger and the vehicle)

- **BEV base case:** Charging overnight, at loading stops (depending on the type of good) and during mandatory driver breaks after 4.5 hours operating time
- **BEV with intermediate charging**: Charging overnight and at loading stops. Intermediate charging is possible at all times. Mandatory driver breaks can also be taken before 4.5 hours of driving, e.g. after 2 hours. If the charging stop leads to an additional time delay outside mandatory driver breaks, a cost penalty of 34 € per hour delay is applied[3].
- **BEV without intermediate charging**: The vehicles can only charge overnight.

For the economic potential of FCEV, we looked at two cases: One with hydrogen from domestic electrolysis and one with imported hydrogen. The potential of overhead catenary trucks includes OC-BEVs and OC-HEVs on two different overhead line network lengths. Figure 3 shows the economic potential of each technology as the share of mileage, where the alternative technology is profitable compared to the diesel vehicle.

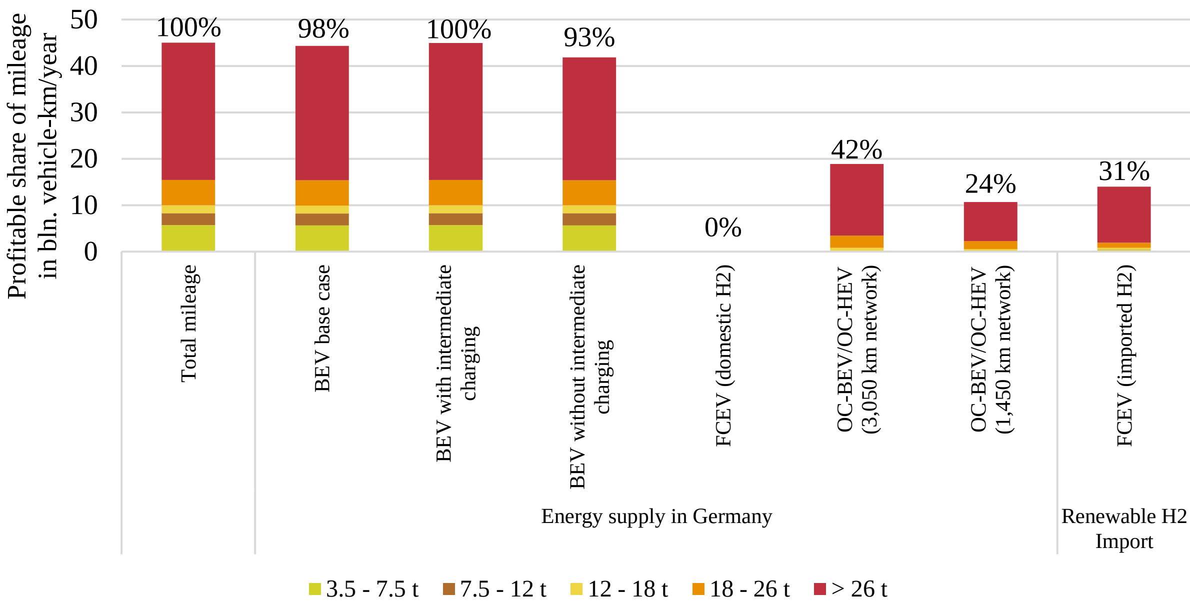

Figure 3: Share of mileage for each drive technology that is economically competitive with conventional diesel technology in 2030 for operation in Germany

The main findings are as follows:

- BEVs show cost advantages (in variable amounts) for almost all application profiles and size classes.
- FCEVs with H_2 from electrolysis based on the expected German grid mix are not economically competitive within the considered timeframe.
- OC-BEV/OC-HEV can have an economic advantage over diesel trucks, mainly on long-distance routes. Their deployment potential then depends mainly on the length of the overhead line network. OC-BEV account for the majority of the OC truck potential while OC-HEV only constitute a small part of less than 10 %, with daily distances > 600 km.
- In the case of very low H_2 costs (4.57 €/kgH2), FCEVs powered by imported H_2 are competitive with diesel trucks for about a quarter of all applications. In this case FCEV show about the same TCO as diesel trucks for about half of the total mileage.

[3] A detailed derivation of time costs is described in [10]

3.2 Cost-optimised drive train portfolio

In a second step, we calculate a cost-optimised drive train portfolio for truck traffic in 2030. To this end, we compared all considered technologies in terms of their TCO at the level of individual vehicle application profiles. An overhead line network of 3,050 km and cheap imported hydrogen (see above) were assumed in this calculation. The results are shown in Figure 4 with and without the assumed infrastructure costs (see Table 2). In the case without infrastructure costs considered, it can be seen that BEVs dominate the resulting technology mix (about 68% of the mileage). On long routes with a sufficient share of overhead lines, they are complemented by overhead line trucks (predominantly OC-BEVs), which can achieve an average cost advantage of about 4 % compared to BEVs. Diesel and fuel cell trucks have minimal shares of less than 1 % in the cost-optimized technology mix. The inclusion of infrastructure costs does not substantially change the overall results: About 85 % of the total mileage show a cost advantage of BEV and OC-BEV over diesel trucks. For less than 5 % of the total mileage diesel trucks are more profitable than the alternative technologies. The results show that in 2030, a much larger share of electric drives for new truck registrations may be expected than what would be needed by the manufacturers to comply with European fleet emission regulation [11][4].

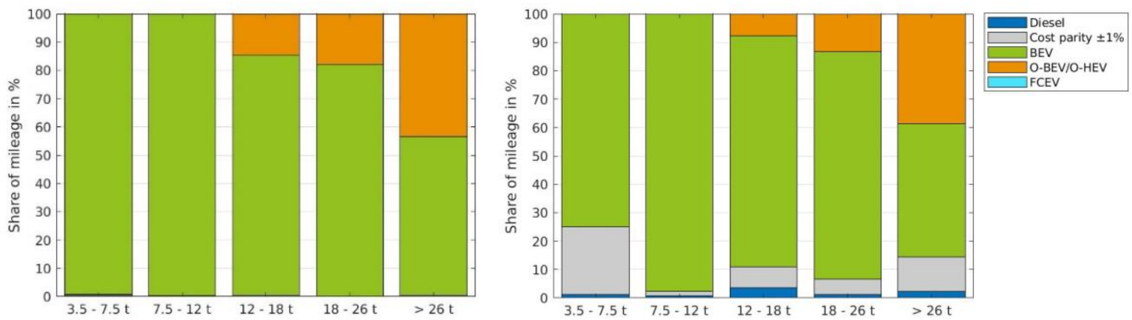

Figure 4: Cost-optimized drive technology mix by vehicle classes for reference year 2030 in Germany (3,050 km overhead line network). Left: Infrastructure costs not considered, right: Infrastructure costs considered

Figure 5: Cost-optimized drive technology mix for HDV > 26 t by daily mileage (3,050 km overhead line network)

[4] The authors of [11] conclude that manufacturers would need a maximum of 22 % of new registrations in 2030 to be zero emission trucks in order to comply with the regulation.

Figure 5 shows the technology mix for the largest size class, broken down by daily mileage. Overhead catenary trucks (OC-BEV in most cases) show cost advantages over all other technologies mainly on long routes. The coverage of each relation with overhead lines plays a major role for the TCO. Higher shares of overhead lines on the route reduce the required battery capacity, hence reduce costs. Furthermore, the assumed charging flexibility of BEV has a significant influence on the relative economic potential of overhead catenary trucks and battery trucks, as Figure 6 shows. Without intermediate charging, the required battery capacity of BEV trucks is much higher on average, making overhead catenary trucks comparably more attractive in many cases. With charging after 4.5 hours of driving or an even more flexible charging strategy and availability, overhead catenary trucks play a less prominent role in the technology mix.

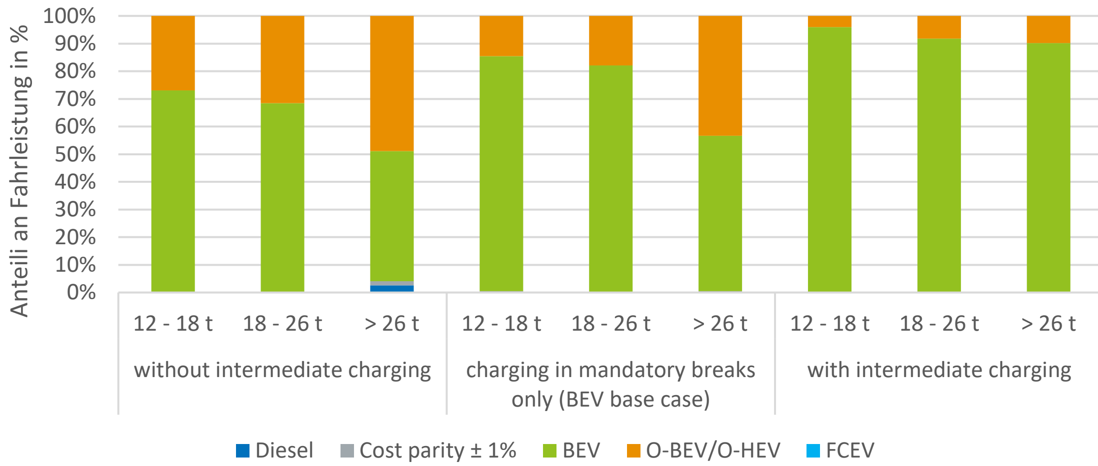

Figure 6: Cost-optimized drive technology mix for three different assumptions on BEV charging availability

Truck operators in Germany can expect annual TCO savings of around 3.5 billion € compared to the reference case, if the cost-optimal technology portfolio is realized (and the framework conditions remain unchanged). If no overhead catenary network is assumed and battery electric trucks are used exclusively, the operators' annual cost advantage is reduced by about 500 million €. The cost savings thus increase with overhead line expansion, but are nevertheless at a similar level, taking into account the uncertainty of the assumptions. A complete allocation of the infrastructure costs to the operators halves the cost savings in all cases.

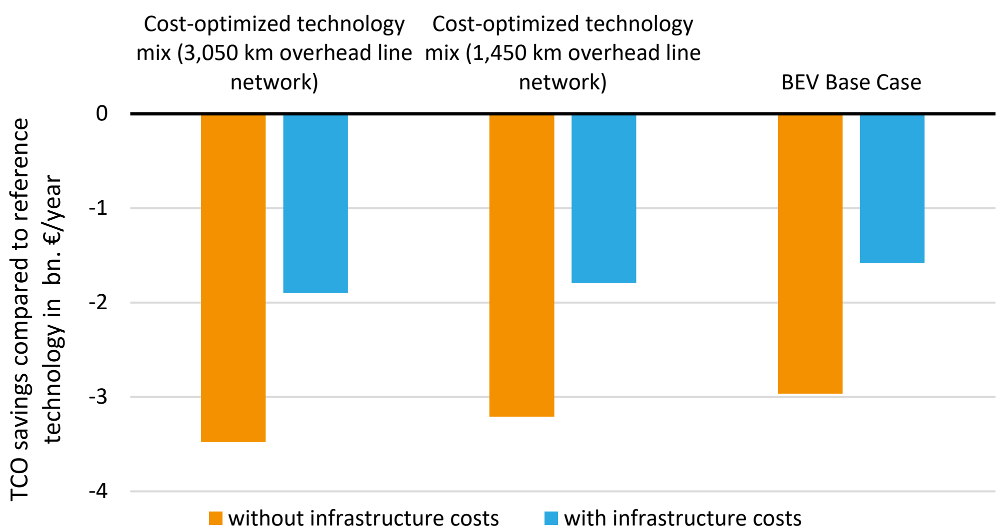

Figure 7: Annual savings for truck operators if the three most cost-effective technology portfolios are implemented (reference year 2030). If the infrastructure costs are allocated to the operators, the savings are reduced to the blue bars (own calculations).

4 Discussion and Conclusions

From the results, we draw the following conclusions for the shaping of the drive train transition in road freight transport:

- The total mileage and the economic potential are dominated by the truck segment > 26 t. For this segment in particular, vehicles and infrastructure for alternative drive systems must therefore be developed in the coming years.
- Battery electric trucks are likely to form the backbone of cost-efficient road freight transport in the future; the results of the study are very robust in this respect. A demand-driven expansion of charging infrastructure in the operational area (especially in depots and at loading bays) should therefore be decisively promoted.
- With public high-power chargers, the use of battery electric trucks for long-distance transport is generally possible, even on longer distances. The required battery electric trucks with ranges of around 500 km could be cost-competitive with diesel trucks in many cases in 2030, although the costs are almost comparable due to the large batteries. Electricity costs, especially for high-power intermediate charging, are an important variable in this context.
- For some of these application profiles, power supply via overhead lines may offer slight cost advantages over the use of battery electric trucks with high-power intermediate charging. Yet both, system costs and GHG emissions (not shown here) of battery electric scenarios with and without the use of overhead lines are relatively close. However, other aspects play an important role in the question of whether overhead lines can be a sensible addition to the power supply for trucks in the future, in particular

    i. operational feasibility and scalability of stationary high-power charging along highways at high penetration rates of battery electric trucks (area availability, operational resilience, grid integration, etc.)

ii. impact on the energy system and the provision of flexibility options

iii. the consequences of different resource demands of the drive technologies and their infrastructure, especially raw materials for batteries

iv. the consequences of longer-term modal shift to rail for sensible final expansion states of road freight transport infrastructures

- The connection of the highway network to the power grid and the large-scale piloting of battery electric and catenary trucks represent no-regret options for government action.
- Fuel cell trucks will probably require continuous government intervention for competitive operation and will in our view therefore only play a minor role in the domestic German transport market. The use of electrolysis hydrogen from national production is not cost-efficient until 2030 and the availability of cheap imported hydrogen from renewable energies must be regarded as questionable in the medium term with respect to a strong competition for use, e.g. in industrial applications or power-to-liquid fuel production for air and sea transport.

The presented results are robust with respect to the economic differences between battery electric trucks (BEV and OC-BEV) and FCEV applications. However, the portfolio, i.e. the optimal share of BEV and OC-trucks in the technology mix strongly depends on the assumptions made, e.g. electricity prices and charging availability (as indicated in Figure 6). Furthermore, we have not looked at the impact of high power and overhead line charging and their temporal load profiles on the electric grid and thus on electricity prices. Our analyses have shown that the economic potential of electric trucks behaves quite sensitive to electricity prices [9]. Even though our calculations go beyond the analysis of average use cases, our assumptions on annual mileage, daily trip lengths, load, operating days etc. cannot cover the wide range of all use cases in road freight transport. These limitations make it very difficult to give a cost-based recommendation as to whether or to what extent BEV or OC-trucks are more suitable for road freight transport in Germany.

Acknowledgments

This work is as part of the project My eRoads, which is funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) as part of the “Erneuerbar Mobil” funding programme under the funding code 16EM4006-1.

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Authors

After completing his master's degree in mechanical engineering at TU Berlin with a thesis on Life Cycle Assessment of Berlin's passenger transport system, Florian Heining joined ifeu in 11/2020. At ifeu, his focus is on cost and emission modelling of alternative drive technologies, analysis of decarbonization measures and sustainability assessment of mobility and housing.