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Heavy long haulage in Germany until 2050 – a System Dynamics modeling approach investigating catenary-hybrid and fuel cell electric trucks

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Summary

Emission-rich heavy long-haulage is a main lever for Germany to achieve its ambitious CO_2 targets, in particular the alternative technologies catenary-hybrid and fuel cell are considered promising options.

This article covers technical characteristics, infrastructure requirements and adoption of new technologies in the market. Truck purchasing decisions, infrastructure expansion and technological improvement are modeled using System Dynamics and thus allow to study different scenarios' effects on society, e.g. CO_2 emissions.

Results show that even under strong incentive schemes mass adoption of catenary-hybrid trucks starts in the late 2020s, high-cost fuel-cell remains a niche technology.

Keywords: fuel cell vehicle, heavy-duty, policy, truck, powertrain

1 Introduction

Climate change as a joint challenge urges each nation to support research on, develop and implement policies targeting 'new and renewable forms of energy, or carbon dioxide sequestration technologies and of advanced and innovative environmentally sound technologies' [29, Article 2]. In addition to the ambitious greenhouse gas (GHG) emission targets Germany agreed on in the Paris Agreement and committed itself to knowledge transfer and pioneering activities on behalf of GHG reduction [30, Article 9-11]. Germany is often perceived as being at the forefront of combatting climate change, however the required reduction of emissions by 80-95% until 2050 compared to 1990 implies a challenging, almost complete decarbonization of its economy and society [5,8].

From 1990 to 2017 GHG emissions in Germany, the emissions were reduced in almost all sectors except from transport, which increased given to the growing road traffic [27]. Accounting for 12.5% of all GHG emissions in 2015 [27], road traffic must be considered a major lever for Germany to achieve its ambitious climate targets. Among road transportation sectors, the technological innovations in terms of emissions were in balance with the additional transportation volume [5, 9], leading to overall stable emissions. The trend of growing transportation volume is expected to continue with a yearly growth of 1.2% for the heavy road transportation segment [5, 32]. In contrast to other transportation segments as, for example, passenger transportation, no technological disruption has been initiated or taken place so far. However, to achieve the decarbonization of the German transportation sector, it will be necessary. Even though this work is focusing on the German market for heavy long haulage, being a transit country as well, Germany will have to come to a European solution with its neighbors and its economic strength going along with a transportation intensity could make it a driving force in achieving such an agreement.

This article contributes to the discussion around GHG emission reduction in the German transportation sector by investigating the effect of governmental incentives to promote alternative drivetrains for heavy commercial transport and their subsequent diffusion in the market. A strong focus of this work lies on modeling market adaption and diffusion of competing technologies by taking into account buyers' decision making process and how it is influenced by following different possible policies. To achieve this aim, the presented results are simulated based on a stakeholder analysis as the foundation for a System Dynamics (SD) model. The presented SD model combines diffusion processes for alternative drivetrains, infrastructure requirements and restrictions as well as weighted criterions for the specific buying decision.

2 Background and methodology

Up to now there is no model considering the diffusion of alternative technologies in the heavy duty transportation sector under the consideration of different stakeholders and the influence of different public policies. This chapter describes how the developed model combines existing approaches and builds a unique combination of them.

Today's standard powertrain in heavy road transport trucks is diesel fuelled combustion engine. Due to lower GHG emissions also several non-internal combustion engine alternatives are under discussion. Most promising to meet the German targets in terms of range, reliability, refuelling speed and energy consumption are catenary hybrid trucks (CHV) with an overhead cable and another drivetrain (battery or diesel) as well as fuel cell trucks (FCEV) [13]. Both technologies are still under development and are only applied in pilot projects so far. For FCEV a pilot project is running in Switzerland and a US-based company presented a prototype and announced large scale production. For CHV three pilots are ongoing in Germany. Due to this early development stage and the expected transition time of several decades [9], a model timeframe until 2050 is reasonable to provide the relevant long-term outlooks. Biofuels as a 'green' replacement for diesel are not further discussed here, as they often compete with food if produced as first-grade fuels [13, 32] and the use of second-grade fuels for trucks is also rather limited. It is unlikely that biofuels can cover all demand from the truck segment, especially as trucks are competing with other offtakers, who have far less alternative decarbonisation options, e.g. aviation.

The diffusion of a technology is strongly influenced by different stakeholders. Information on the main stakeholders involved in the diffusion of alternative powertrains in the long haulage segment was gathered through stakeholder analysis, which is proven to be a fruitful method in public policy and management environments [10]. This comprised stakeholder identification, differentiation and classification [23], which was conducted by an expert focus group. Results are documented in an interest-influence matrix [4, 11] as well as an actor-linkage matrix [4], both are commonly used techniques in stakeholder analysis [11, 23].

The core aspects identified through this analysis became part of the SD model. Forrester developed SD in the 1960s based on system theory and control technology and SD became known to a wider audience when the study 'The limits to Growth', which deploys SD, was published for the Club of Rome in 1972. SD is a 'practical profession' [12] which 'abstracts from single events and entities and takes an aggregate view concentrating on policies' [6]. Being fundamentally interdisciplinary it is a 'perspective and set of conceptual tools, which enable us to understand the structure and dynamics of complex systems' [26]. The congruency of SD with the subject of this research in terms of aims (depiction of long-term development of complex cause and effect relationships) led to wide applications of this modelling approach for fleet research questions (see e.g., 3, 22, 24, 31). From its very beginnings SD focused on business and public policy applications, especially for the discussion of scenarios with yet unknown 'irreversible consequences' [26]. Technology diffusion has been widely studied and has its roots in first diffusion models by Bass [1] and Milling [21], enriched by Maier's [19] approach to model various competing technologies. [25] summarizes SD applications for vehicle fleet research and [20] provides a meta-overview of parameter estimates for the diffusion of alternative powertrains.

For SD models focusing on technology diffusion in the automotive market it is necessary to model the purchasing decision of buyers in detail, where discrete choice models are capable of depicting the individual choice by dividing it into the steps '(i) choice set generation; and (ii) choice from a given choice set' [2]. Choice sets consist of the different technologies and their respective characteristics in terms of capital costs, fuel costs and availability of suitable infrastructure, which develops over time depending on the stock of vehicles per technology. The choice (driven by purchasing probability) depends on the customers' awareness for the technology (modeled with the Bass diffusion model) [31]. By using discrete choice theory both customers' preferences and powertrains' characteristics can be considered [28].

3 Methodology

This approach uses SD modelling to combine and integrate the techno-economical aspects of the powertrains, the interlinkages between the stakeholders and their preferences as well as to simulate the effect of different policies. The methodology and model development follows the modelling process as defined by Sterman [26]. Despite being a fundamentally iterative process, only final stage results are presented in this article. The step of Problem Articulation was conducted in section 1, the Dynamic Hypothesis is explained in the following paragraphs. Final results of Formulation are shown in the Modeling section. Testing was conducted, but would exceed this article's scope. Results of Policy Formulation & Evaluation are discussed in section 5.

The final model consists of five parts with subordinate modules within each, as shown in Figure 1. Exogenous developments comprises price and efficiency developments, mostly linked to global sales and international research efforts and thus considered beyond the boundaries of this model, i.e. as externally given.

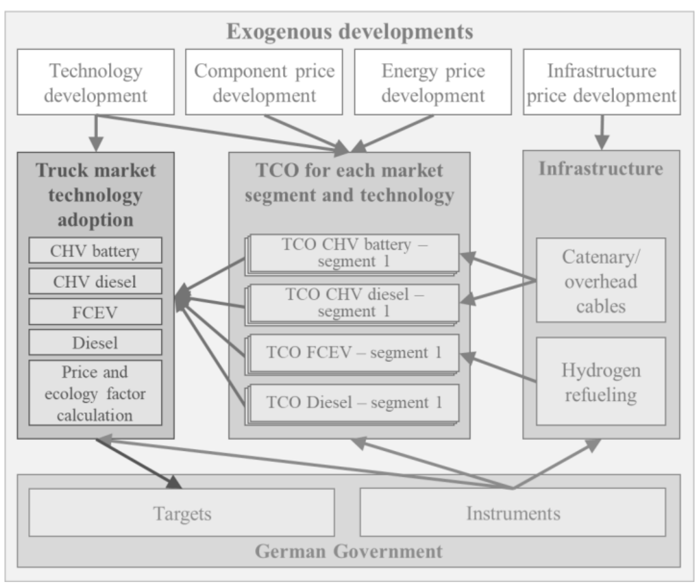

Figure 1: Components of the model – schematic representation

Within truck market technology adoption the final product adoption is simulated. Thereby for truck purchasers the costs are considered as the most important decision criteria complemented by rather soft criteria such as environmental concerns [18, 24]. Cost (in the model represented by total cost of ownership (TCO)) and environmental issues (GHG emissions in the model) are given a weighting of 90:10 [18]. Additionally, a minimum required infrastructure has to be assumed for FCEV and CHV battery to enable a diffusion (gas stations offering hydrogen and kilometres of highway equipped with catenary). In order to take these newly emerging technologies into account in their purchasing decision process, logistics service providers have to be aware of them when they take such a decision. This awareness is modeled with diffusion process similar to the Bass diffusion [1].

As described in the previous section, the costs are a major criteria for the diffusion of alternative powertrains. The section TCO for each market segment and technology therefore calculates costs for all technologies since truck buyers commonly base their purchase decision on such considerations [7, 13]. Among these costs are component prices (e.g. chassis), capital costs, fuel costs, tax, toll and purchasing premiums or penalties offered by the government. Costs which are equal for all technologies such as driver costs are not included.

The infrastructure part is required in order to model the effects emerging from infrastructure coverage and market diffusion [16]. This module depicts the hen-egg paradox of new technologies and their infrastructure. As pointed out by [32] a well-penetrated market would be able to finance the required infrastructure but the challenge lies within the infrastructure ramp-up during the market growth phase.

Within the German government section, target categories (GHG emission reduction, financial implications and additional power demand) are monitored and public policies are configured. [15] strengthens the governmental role in new technology diffusion processes: 'to successfully commercialize technology, the infrastructure, competitive factors and other components of the selection environment must be changed. Government strategy should (…) be a regular part of market transactions' (ibid.) resulting in the close linkages to the other parts of the model.

4 Modeling

The parts and modules described are implemented using the SD software 'Vensim'. This section focuses on the implementation of core aspects of each of the previously presented parts. Variables, which are explicitly mentioned, and formulas from the model are highlighted in a different font.

4.1 Exogenous developments

Within the module technology development, the technological progress of different technologies resulting in efficiencies is modeled based on [13, 32]. The second module, component price development, covers the price development for motors, tanks, battery and further equipment needed for any of the technologies. A non-linear decay approximation is used for these variables except from diesel motors, as technology improvement, learning effects and economies of scale can be expected [7]. In the energy price development module all energy carriers' prices (electricity, hydrogen and diesel) are expressed as exogenously given developments.

Infrastructure price development is externally given and covers both installation and maintenance cost information. Values are derived from different literature sources. For the catenary overhead solution €2.2 million per km are assumed as installation costs (material and work). Most sources indicate a range from €1.1 to €3.0 million [7]. Data on costs for installing hydrogen refueling stations for heavy commercial vehicles is also rather scarce thus the installation price used in the model is estimated based on available information for passenger car refueling: on average 60 kg hydrogen is needed to refuel a truck. Refueling stations vary in their size and thus for example the H2Mobility initiative segments them from very small to large, with 1,000 kilograms being the largest passenger vehicle refueling station size. Thus for commercial vehicle refueling stations a capacity of 1,500 kilograms is assumed. With a scaling factor of 0.7, learning rate of 6% and 30% additional installation cost, this results in €3.58 million for a refueling station. Additionally, a cost digression of 3% per year is also considered as well as maintenance costs of 3% of the installation costs.

4.2 Truck market technology adoption

The semi-trailer truck market is expected to grow in the next decades [32] and replacement purchases will take place. Therefore the model bundles them to one truck market demand. Within the truck market three different segments are identified based on the motor vehicles in Germany 2010 data [33], the main source for truck driving data in Germany [32]. Semi-trailer trucks are segmented according to their primary area of operation. Based on 260 operational days per year the average yearly mileage is determined for each segment. Additionally, the share of highway usage was estimated based on a non-linear fit [33]. For later TCO calculations (incl. tolls and fuel consumption) the share of kilometers driven on highways is considered and an equal infrastructure development in neighbouring countries is assumed. Using average values to describe such segments and use it in the model is a common practice [5]. The resulting segments are shown in Table 1.

Table 1: Model parameters – Truck market segmentation

	Segment 1: within Germany, mainly urban and rural	Segment 2: within Germany, mainly on highways	Segment 3: international, mainly on highways
Market share	18%*	67%*	15%*
Average daily mileage	223 km	362 km	445 km
Average yearly mileage	57,936 km	94,247 km	115,647 km
Share of highway usage	15%	95%	95%
Average yearly mileage driven on highway	8,690 km*	89,534 km*	112,139 km*

Logistics service providers aim to minimize TCO under a given driving profile (here represented by the segments). TCO then determines technology. During the screening of different technologies, not only the number of trucks within his segment using the technology, but the overall popularity of the technology determines how many logistics service providers are actually aware of the technology and thus can consider it in their decision.

For that reason each technology module models the adoption of the same three truck segments. A prerequisite for the adoption of any technology is the awareness for the latter. As in [31], the Bass diffusion model is used for this purpose. The Bass model [1] splits potential future customers in two groups: innovators and imitators. Innovators 'become aware of the innovation through external information sources whose magnitude and persuasiveness are roughly constant over time' [26]. Imitators are influenced in their purchasing decision by their social environment and the overall market share of the studied technology, meaning the more people already have adopted the technology, the more likely an imitator is to adopt it as well. Bass [1] and Sterman [26] elaborate on the mathematical formulation of the interrelations used for this model and [20] gives an overview on its application, e.g., passenger cars in Brazil [3], trucks in Germany [24], FCEVs in Korea [22]). Based on utility, a combination of the technology's price and ecological attractiveness, its market share is determined. The market share, again, grows with new adoptions and gets reduced by scrapped trucks.

The module 'price and ecology factor calculation' assesses the price and ecological attractiveness of each technology in each segment based on TCO and including governmental incentives such as purchasing premiums. For CHVbattery and FCEV the minimum infrastructure has to be installed to make them eligible options, CHVdiesel are able to start operating with very few kilometers of highway equipped with overhead cables and diesel does not need any new infrastructure.

4.3 TCO for each market segment and technology

Table 2: TCO – cost components and yearly costs

	CHV battery	CHV diesel	FCEV	Diesel
Yearly costs	fuel: electricity; CO_2 certificates; toll; capital costs (decreasing over time)	fuel: electricity; fuel: diesel; CO_2 certificates; toll; capital costs (decreasing over time)	fuel: hydrogen; CO_2 certificates; toll; capital costs (decreasing over time)	fuel: diesel; CO_2 certificates; toll; capital costs (decreasing over time)
One-off costs	truck chassis without motor; electric motor; battery; pantograph; additional tax on CHV battery purchase	truck chassis without motor; electric motor; diesel motor; pantograph; additional tax on CHV diesel purchase	truck chassis without motor; electric motor; fuel cell; hydrogen tank; additional tax on FCEV purchase	truck chassis without motor; diesel motor; additional tax on CHV battery purchase

For TCO calculation, 12 TCO modules are run: one for each market segment and technology combination. Table 2 shows the technological components and yearly costs taken into consideration in the TCO calculation based on literature values [7, 32]. Additionally, inputs from the 'technology development' module are used such as increasing efficiency of engines reducing the fuel per kilometer needed.

4.4 Infrastructure

Both potentially needed infrastructures - a hydrogen refueling network or catenary cables on highways - are modelled in a specific section. Main influence factors are: installation costs, ramp-up of the infrastructure, maintenance costs and lifetime of these infrastructures. Additionally, the financial flows including governmental subsidies or infrastructure programs are included in the loop, as the SD visualization Figure 2 shows.

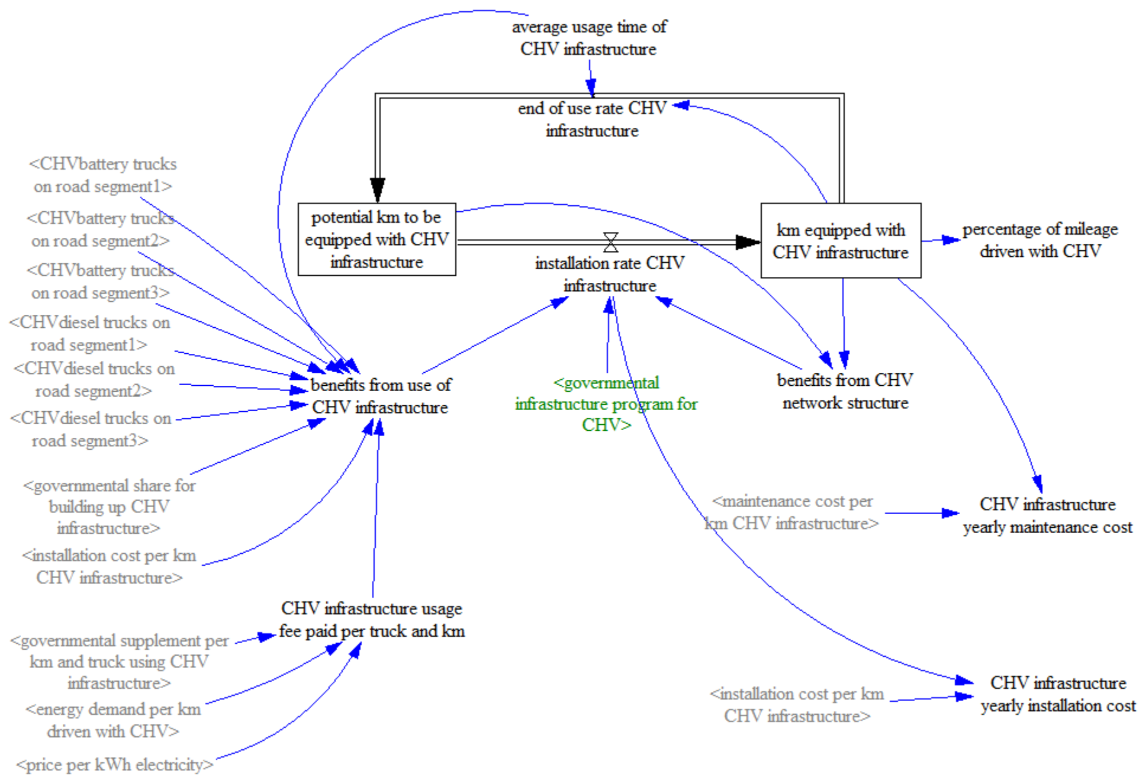

Figure 2: Catenary cable infrastructure

The entire German highway network could potentially be equipped with catenary infrastructure. However, it is economically most beneficial only to electrify the most frequently used parts of the network and thus achieve high network coverage while limiting infrastructure costs. Depending on the expected benefits from installation (driven by number of vehicles using it, a governmental support for installation, size of the existing network as well as direct government programs for building the infrastructure), more or less additional kilometers will be equipped with the needed infrastructure every year. The more kilometers of highways equipped with catenary infrastructure, the better they meet driving profiles of trucks and more CHV can drive with their electrical drive, but also the higher yearly maintenance costs are. After an average lifetime of 20 years, infrastructure reaches its end of life and can again either be potentially equipped with new catenary infrastructure or not.

Non-diesel-based technologies require a minimal installed infrastructure in order to enable an initial operation: For CHV battery 1,960 kilometers equipped with overhead cables are assumed. Analyzing routing data of heavy duty vehicles [32] showed that this infrastructure coverage would be enough to allow for 38% of the truck traffic to switch to CHV technology. For FCEV the network of gas stations has to be considered. On average there is a gas station every 37 kilometers on German highways today [14]. Assuming the same distance coverage as for CHV battery, 53 existing gas stations need to provide hydrogen refueling or be completely new installed.

4.5 German government

To support the transition to alternative drivetrains the government's role in the future might need to change from a regulator to a more active one as an enabler or catalyst [17]. Thus, understanding the effects of each instrument in the governmental toolset is essential to pursue a public policy effectively reducing GHG emissions in long haulage transport.

For the model different public policies affecting the heavy-duty commercial vehicle segment are analyzed. The measure can be defined along five dimensions:

- Technological focus: open-technology approach or focus on one single technology (CHV or FCEV)
- Time horizon: short-term (<10 years), long-term (>10 years) or both
- Instruments targeting purchasing decision: purchasing premium, purchasing penalty
- Instruments targeting TCO: usage independent (vehicle tax), usage dependent (toll fee adjustments)
- Instruments targeting infrastructure: co-financing with private investors (PPP) or government as stand-alone investor (thus covering full cost of installation and maintenance).

In this part of the model the effect on the governmental target categories (GHG emission reduction, financial implications and additional power demand) is calculated. The respective indicators for all technologies t (with 1=CHV battery, 2=CHV diesel, 3=FCEV and 4=Diesel), infrastructure technologies i (Catenary and Hydrogen) and all segments s are calculated as follows:

Total GHG emissions per year [kg CO_2e] are calculated by the sum of each technology in each section:

$$Total\ emissions\ per\ year = \sum_{s=1}^{3} \sum_{t=1}^{4} yearly\ emissions_{s,t} \tag{1}$$

Financial impact of government instruments targeting infrastructure investments (f_{inf}) are determined by the units (km of overhead cables installed or number of gas stations) multiplied by investment per new unit and the share of governmental contribution in case of a public private partnership (PPP). Additionally, the government may make payments to private companies which built the CHV infrastructure. This payment consists of the CHV supplement per km and truck (in addition to the usage fee the truck owner pays) multiplied by the number of trucks using the CHV infrastructure and their yearly mileage using this technology [€]:

$$f_{inf} = -\left(\sum_i infrastructure\ cost\ per\ unit_i \cdot (infrastructure\ program_i + governmental\ share_i \cdot PPP\ infrastructure\ building_i)\right) - \left(CHV\ supplement \cdot \sum_{t=1,2} \sum_s \left(trucks\ on\ road_{t,s} \cdot yearly\ mileage\ on\ highways_s\right)\right) \tag{2}$$

From technology purchases, an income for the government could be generated by introducing a penalty for the purchase (purchase penalty) of conventional diesel combustion engines. On the other hand purchasing premiums paid for the purchase of alternative drives (both CHV and FCEV) multiplied of the actual adoption rates for each of them result in expenses for the government. The technology purchase impact (f_{tec}) is therefore described as follows [€]:

$$f_{tec} = \left(purchasing\ penalty_4 \cdot \sum_s adoption\ rate\ truck_{s,4}\right) - \left(\sum_{t=1}^{3} \left(purchasing\ premium_t \cdot \sum_s adoption\ rate\ truck_{s,t}\right)\right) \tag{3}$$

Yearly incomes for governments are created by an additional tax per diesel truck on the road, tolls paid and CO2 certificates purchased by each truck depending on the emissions it causes are summarized as yearly costs (f_{cos}) [€]. Partially they are negative and thus an income for the government [€]:

$$f_{cos} = \sum_t \left(additional\ tax_t \cdot \sum_s trucks\ on\ road_{s,t}\right) + \sum_t \sum_s \left(trucks\ on\ road_{s,t} \cdot toll\ costs\ per\ truck_{s,t}\right) + \sum_t \sum_s \left(trucks\ on\ road_{s,t} \cdot CO2\ certificate\ costs\ per\ truck_{s,t}\right) \tag{4}$$

These three factors (2 – 4) result in total financial implications per year [€]:

$$financial\ implications = f_{inf} + f_{tec} + f_{cos} \tag{5}$$

Finally, the total electricity demand per year [kWh] is calculated by the sum of each technology in each segment:

$$Total\ electric\ energy\ demand\ per\ year = \sum_{s=1}^{3}\sum_{t=1}^{3} yearly\ electric\ energy\ demand_{s,t} \tag{6}$$

5 Results for heavy-duty vehicles and discussion

Effects of different policy instruments on the target categories are analyzed via different scenarios, here understood as coherent pictures of a possible future. For this model in addition to the base case five scenarios are defined addressing the different possible dimensions of policies as shown in Table 3. Instruments were then calibrated accordingly, to account for time horizon and technological focus of each scenario. All measures are expected to start 2020 (t=3 in the model) earliest, due to required political approval processes.

Table 3: Scenarios' focus

	Base case	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Technological focus		CHV	CHV	Open	FCEV	FCEV
Time horizon		Short-term	Long-term	No focus	Short-term	Long-term

The direct impact of policies on the number of vehicles using a specific drivetrain can be observed in Figures 3 to 6. CHV diesel (Figure 4) can be seen as a technology bridging the CHV technology gap until the infrastructure coverage is good enough to sustain CHV battery (Figure 3). Additionally, it might become even cost-competitive without governmental support, as the late but impressive growth of this technology in Scenarios 4 & 5 shows. Figure 5 points out the main challenge FCEV sees: their comparatively high TCO means, they only get bought in scenarios where they are heavily promoted. In Figure 6 it can be seen that in all scenarios the number of diesel trucks reduces, but they differ significantly in the speed of doing so: Scenarios including CHV vehicle promotion are much more effective in doing so and could reduce the absolute number of diesel trucks deployed in the heavy long haulage segment by 50% until 2050 mainly driven by their replacement by CHV trucks. In Figures 3 & 4 it can be seen clearly that CHV technologies start their growth once the infrastructure for them is in place.

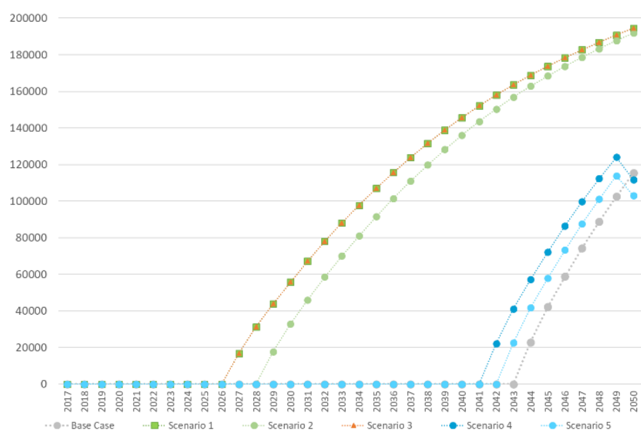

Figure 3: Number of trucks using CHVbattery

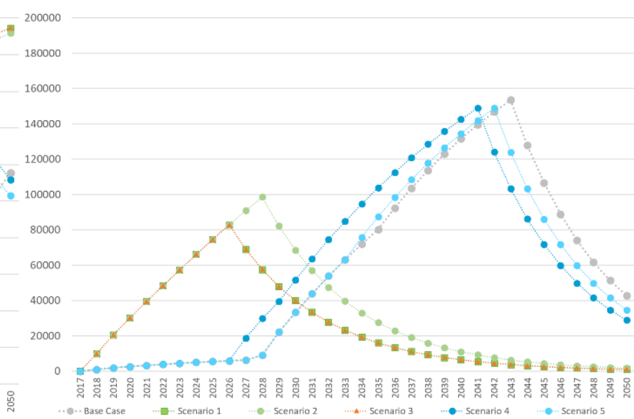

Figure 4: Number of trucks using CHVdiesel

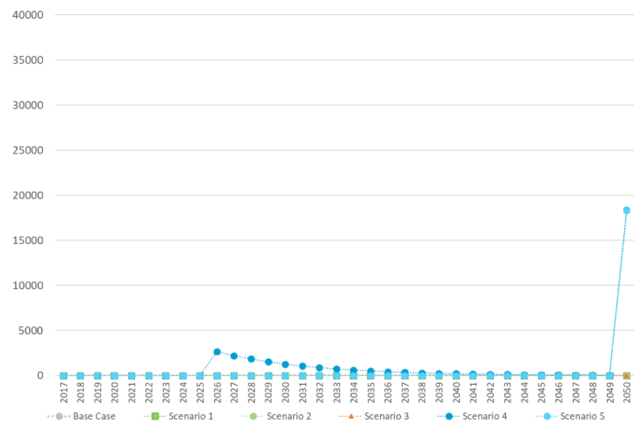

Figure 5: Number of trucks using FCEV

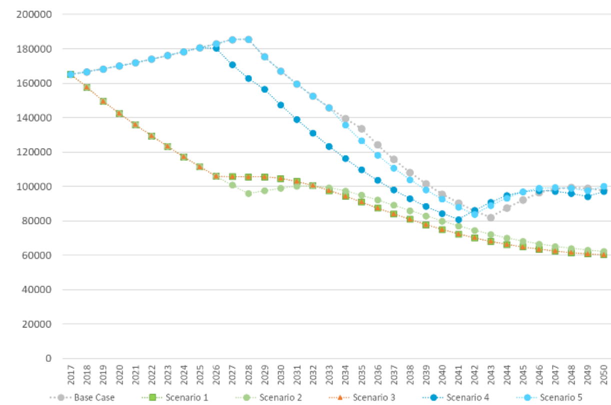

Figure 6: Number of trucks using (conventional) diesel

The effect of the truck numbers' developments is shown in Figure 7: public policy scenarios incentivizing the purchase of CHV technology are able to significantly reduce the GHG emissions much earlier than those promoting FCEV. FCEV becomes effective much later and not at large scale as a comparison to the base case shows. The scenario promoting both technologies (Scenario 3) shows the best performance in terms of GHG emission reduction, however, it is very close to the CHV-only-promoting scenarios (Scenario 1 & 2). Main reason for this behavior is – as all other scenarios show – the lower threshold of infrastructure investment needed to make CHV cost-competitive versus FCEV achieving cost-competitiveness.

The successful diffusion of CHV goes hand in hand with an increasing demand for power. Scenarios promoting a strong growth of alternative drivetrains (Scenario 1-3) will reach up to additionally required 20 TWh per year by 2050, highlighting the known fact that additional power is required to support a technological shift in the German heavy long haulage segment.

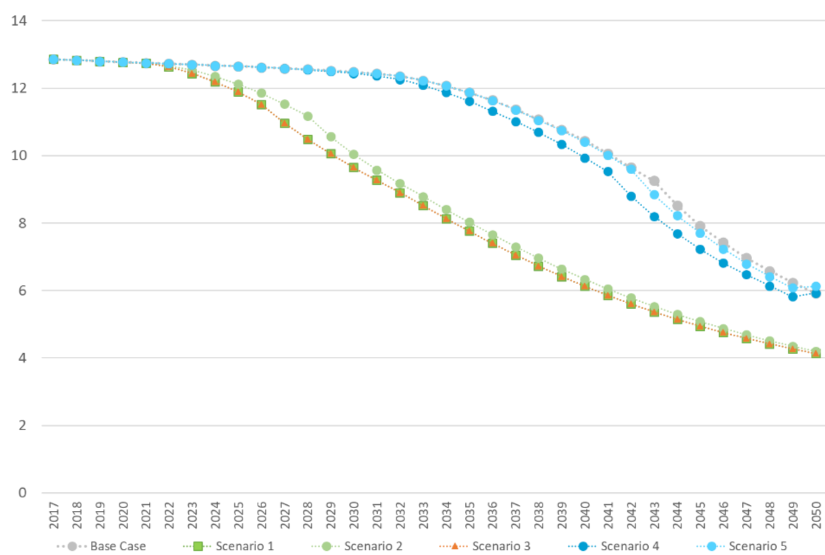

Figure 7: Emissions in all scenarios and base case until 2050 [million tons CO_2e]

From a financial perspective CHV-promoting scenarios 1-3 have high investment needs until the required infrastructure coverage is achieved, thereafter governmental income increases again yet remaining below the base case. In FCEV-promoting scenarios the government's income loss is lower, mainly given to the low number of FCEV and subsequently lower expenditure on purchasing mechanisms. Additionally the number of diesel trucks remains relatively high in those scenarios (3 & 4), so income from toll and high-tax diesel remain high compared to the CHV-cases where the number of diesel trucks was dramatically reduced until 2050.

It must not be forgotten that any model is also highly dependent on its boundaries: the study was limited to the geographical scope of Germany and heavy duty commercial vehicles for road transport. Sensitivity analyses for input factors have shown, that the weight of ecological vs. economic interests in the purchasing decision of logistics service providers have a significant effect in the Base case (lower weight of ecological interests leading to much lower adoption). However, if incentive schemes are put in place (such as in Scenarios 1-5), these are able to overcome this weighting, meaning: by setting an appropriate public incentive scheme the individual weighting of ecological vs. economic benefits of logistics service providers can be eliminated, so public policy can translate common ecologic interests to economic incentives for a specific groups. The model shows that component and infrastructure costs are essential for the diffusion of technologies. Current cost assumptions might become outdated due to new developments such as a new investment wave targeting hydrogen technologies or new production methods resulting in significant cost reduction, so an update for future studies could be required.

Further studies might shift their focus to trans-national and cross-segment synergies or expand their scope beyond the heavy-duty commercial vehicles. Additionally, this article focuses on an explorative approach, implying that the orchestration of governmental instruments was not optimized. Moving forward to further detailing of the public policy such studies on optimal financial incentive structure and timing constitute an important starting point for future work be conducted.

6. Conclusion and Policy Implications

Key findings of this study are:

- The highest emission reduction potential is achieved by promotion of CHV-technologies.
- Any scenario studied does not meet the GHG reduction targets of -80 to -95% by the German government. Further ambitions are needed.
- Demand for power from renewables for powering trucks is expected to increase to 15-20 TWh until 2050. This development has to be considered in further efforts regarding sector coupling and promotion of renewable power generation technologies.
- Effective measures will go along with significant costs especially for infrastructure and resulting in potentially less income for the government (under stable framework conditions).
- CHV diesel can be seen as a bridging technology from conventional to CHV battery and it appears as such in all studied cases.
- FCEV will only be adopted after 2040 if no governance action is taken. Main reason for that are high technology costs (e.g. fuel cell itself) and refueling infrastructure.
- (Conventional) diesel will not be extinct by 2050, however, there is a possibility to significantly reduce its market share despite an overall growth of the heavy haulage sector.

Results show the potential to significantly reduce GHG emissions by providing infrastructure and a suitable incentive scheme to promote alternative technologies. The volume growth in this sector makes it a particularly pressuring task and thus the German government should develop suitable public policies. The model showed that infrastructure is a key for both, CHV and FCEV, drivetrains and diffusion of alternative technologies to diesel is highly dependent on the fast development of infrastructures. Thus, investments should be given high priorities in the next decade. Additionally, results show that any ambitious technological shift still is not enough: switching to other modes of transport and reducing or further optimizing the overall transport volume must complement the introduction of alternative drivetrains in order to have a chance to meet Germany's ambitious climate targets. Otherwise the missing gap must be closed by the smaller vehicle classes, where FCEV or full battery electric driving can be enabled easier.

The studied SD model shows how - even when implementing extensive and ambitious measures – large the gap between defined targets and real-world developments are. By doing so it underlines the urgency to target heavy road transport in Germany with a well-thought through public policy. By showing the late developing competitiveness of FCEV the model also gives a first indication which technologies might offer the highest potential in such a public policy.

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