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Market Penetration of Alternative Powertrain Concepts in Heavy Commercial Vehicles: A System Dynamics Approach

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Diffusion of alternative powertrain concepts in heavy commercial vehicles will start in the upcoming years after electrification and natural gas engines have already been introduced for passenger cars. Numerous quantitative forecasting and technology diffusion models exist for passenger cars but cannot be transferred unchanged to heavy commercial vehicles. A system dynamics model for the diffusion of alternative powertrain concepts in heavy commercial vehicles is developed by adaptation of existing simulation models for passenger cars. The structural validity is assured by changing the structure and parameterization based on stakeholder interviews, secondary studies, and theoretical foundations. The results reveal the significance of a satisfying refueling infrastructure for alternative fuel trucks and the transitional market potential of hybrid electric trucks. The discussion of the system dynamics model emphasizes the analysis of customer demand as an essential field for future research of alternative powertrain diffusion in heavy commercial vehicles.

Keywords: technology diffusion, system dynamics, market penetration, alternative powertrain concepts, heavy commercial vehicles, organizational adoption of innovation

1 Introduction

The diffusion processes of alternative powertrain technologies are widely studied based on the example of passenger cars (PC) and, partly, light-duty-vehicles. The prospected market penetration of low carbon technologies within automotive vehicles provides a solid basis for forecasting future greenhouse gas (GHG) emission levels of individual passenger transportation. In contrast, the road freight and public passenger transportation is not widely understood, despite it is a main originator of GHG emissions. Heavy commercial vehicles (HCV) are not part of any – to the best of our knowledge – quantitative forecasting method or technology diffusion model. This might be caused by the dominating Diesel powertrain technology or the different industry structure. Nevertheless, a transition towards alternative powertrain concepts can be expected in the upcoming years due to political will and customer demand: an increasing cost pressure forces transport companies to minimize their fuel expenditures and the European Commission will propose a strategy targeting fuel consumption and CO_2 emissions from heavy and medium duty commercial vehicles to push low carbon transportation (European Commission, 2011, 2012).

Quantitative forecasting methods for the transportation system are mainly based on system dynamics (SD), agent-based modeling or diffusion and times series models (Shafiei et al., 2013; Al-Alawi & Bradley, 2013). System dynamics is particularly suitable to study the fundamental market dynamics and understand the interdependencies of influencing factors. Thus, this method is assumed to be appropriate for levering the basic understanding of emerging technologies' diffusion processes on the HCV market. Since empirical data for the heavy commercial vehicle market are equally rare, a transferred model from the PC market could provide a basis for future research to predict market penetration of low carbon technology on this market as well. Nonetheless, this transferred model should be discussed considering some fundamental differences caused by the business-to-business (B2B) HCV market structure and specific customer requirements.

From a mathematical perspective, such system dynamics' models are simulation models of nonlinear, coupled differential equations (Sterman, 2000). Therefore, one major challenge in implementing SD models lies in the formulation of the mathematical equation representing the empirically observable reality: this represents the heuristics of the problem at hand. Although Sterman, for instance, claims there are no valid models, verification tests help developing confident and reliable SD models (Sterman, 2000). These tests can be clustered into direct structure tests, structure-oriented behavior tests, and behavior pattern tests. Direct structure tests draw comparisons between the market model, represented by the system of differential equations, and the reality. Structure-oriented behavior tests involve simulation of the whole model as well as decoupled sub-models of it and yield to evaluate the model generated dynamics. Behavior pattern tests use graphical and visual measures to compare typical behavior features (Barlas, 1996).

Against this background, the objective of this article is to discuss the application of existing PC system dynamics models aiming to forecast the market penetration of powertrain technologies to the HCV market. This is primarily under consideration of the structural model validity to provide a basis for future research. The SD model is exemplarily developed for the German HCV market. A thorough discussion of the HCV market itself is not intended. It's rather the question whether existing simulation models of the PC market are transferrable to the HCV market, providing an appropriate approach for future research. Thus, the remainder of this article is organized as follows. The second section provides the theoretical foundation of the HCV market simulation model. In section 3 the market model framework is developed by the adaptation of existing SD models for the PC market. Section 4 discusses the simulation model in terms of validity and the implication of the results. A conclusion for stakeholders and future fields of research for HCV market technology diffusion models is drawn finally in section 5.

2 Theoretical foundations for the simulation of powertrain technology diffusion in HCV markets

2.1 Simulation models for powertrain concepts on the passenger car market

There are multiple research streams about automotive market modeling by means of system dynamics. These cover different aspects regarding the technologies to be analyzed (fuel cell vehicles, electric and hybrid electric vehicles, natural gas vehicles), the stakeholders considered (customer, filling stations, energy supply system, manufacturer, government, dealer), the country specific market and the aimed scope (market penetration of technologies, total market sales, overall fuel demand or GHG emissions, policy deployment, manufacturer's actions) (Shafiei et al., 2013). Targeting this paper's aim, we primarily focus in the following on SD models dealing with diffusion processes of alternative powertrain concepts.

Besides some strongly explorative SD studies by two master theses from MIT, Struben was among the first developing a SD model for examining the market diffusion of alternative fuel vehicles. The original work about the diffusion of fuel cell vehicles in California was gradually expanded and applied to other powertrain concepts. These models put special emphasis on the spatial disaggregation of the fuel demand and the corresponding refueling infrastructure. Additionally, the buying process is discussed in detail, using a multinomial logit choice model (MNL) and the construct of "familiarity" by social factors as media attention, marketing effectiveness, and word-of-mouth (Struben, 2004, 2006; Struben & Sterman, 2008).

For the European PC market Janssen identified the most influencing stakeholders on the diffusion of natural gas vehicles in the Swiss car fleet. "Customers sector", "filling station sector", "car import, retail, and service sector" are modeled as endogenous stakeholders, whereas the government, natural gas industry, and "non-Swiss car industry sector" are considered as exogenous stakeholders. In his analysis he described the effectiveness of policy actions on the diffusion of natural gas and fuel cell vehicles. The system dynamics model implementation, calibration, and validation is predominately achieved by dynamic test runs of model modules, which have been primarily derived by empirical observations (Janssen et al., 2006; Janssen, 2005).

Bosshardt expanded the work of Janssen by integrating competition between alternative powertrain concepts and analyzing multiple European markets. Thereby he regarded aspects of cost, availability of car models, refueling infrastructure coverage, powertrain attractiveness, and social norm. The model is used for analyzing the influence of different strategies enhancing the diffusion of alternative powertrain concepts. Validation of the SD model is achieved by graphic representation and subsystem tests, extreme condition tests, sensitivity analysis, and a mathematical analysis of the "social norm loop" (Bosshardt, 2009; Bosshardt et al., 2007).

Keles et al. analyzed the market penetration of fuel cell vehicles in Germany based on the action of different stakeholders. They focused on the interactions of consumers, automotive manufacturers, filling station owners and policymakers. Subsequently, they implemented a "fuel cell vehicle demand and supply module", a "filling station module", an "attractiveness module" and the resulting governmental "balance of payment". Thereby, they distinguished between the available urban and highway refueling infrastructure, latter being dependent of the urban ones. A profound discussion of the model validity is not provided (Keles et al., 2008).

Mainly based on the work of Struben and Janssen, Weikl simulated the future market shares of alternative powertrain concepts for the German market. He put special emphasis on the emotional powertrain related buying criteria in the decision process of new car buyers. Additionally, he aimed to model the manufacturers' actions to improve the characteristics and availability of alternative powered PC models in detail. The validity of the model is discussed by structure and behavior pattern tests (Weikl, 2010).

Recently, Keith extended the work of Struben by incorporating effects of supply constraints of alternative powertrain concepts. Thereby, the scope of platform models availability that is negatively influencing the market share was introduced similar to the work of Weikl. However, the utility reduction perceived by customers and that is caused by missing models of an emerging powertrain concept in all market segments is considered by an exogenous logistic form. Additionally, he discussed the future role of hybrid vehicles as a transitional technology and the spatial diffusion of alternative vehicles (Keith, 2012).

To summarize, existing SD models for the diffusion processes of automotive powertrain concepts essentially comprise four main feedback loops: Infrastructure, familiarity (or social norm), technology attractiveness, and vehicle model availability. Additionally, there are exogenous factors, which comprise governmental actions, international energy prices, and societal trends. This principal setup of common standard structures of alternative automotive powertrain technology diffusion should form the basis for the HCV market as well. Nevertheless, adjustments are required to furthermore assure the structural validity of the SD model.

2.2 Organizational adoption of emerging technologies in HCVs

Bearing in mind the different structure of the HCV market as a B2B industry, some general aspects should be taken into account when transferring the main feedback loops from the PC to the HCV market.

On the one hand, organizational buying processes are different to individual ones. On the other hand, diffusion of emerging technologies takes place in a setting of organizational rather than individual adoption of innovations. Organizational adoption is principally influenced by the environmental context, the organizational context, and the perceived technological characteristics (Rogers, 2003; Frambach & Schillewaert, 2002; Tornatzky & Fleischer, 1990). This is predominantly congruent to individual adoption processes and fits to existing SD models for the PC market: Infrastructure density, technology attractiveness, and vehicle availability affect both the environmental context and the perceived technological characteristics. Additionally, Frambach & Schilleweart stresses the relevance of the social network as well as the observability of an innovation (Frambach & Schillewaert, 2002). Thus, aspects of familiarity should play a role in this context as well. At the same time, organizational buying is primarily dominated by the process orientation of companies. Bänsch mentioned four generic criteria to differentiate organizational from consumers' buying behavior: higher specifity of demand, higher number of persons involved, stronger tendency towards rationality, and a longer purchase decision process (Bänsch, 2002).

Summarizing differences of the HCV and PC market regarding buying and adoption processes, customers on the HCV market are assumed to act generally more rational in aspects of costs and suitability to the transport task. Nevertheless, familiarity affects the buying process by the awareness of the people involved within the process and the observability of new products or technologies. At the same time the organizational processes differ from company to company. Same applies to the organizations' size, structures, and slack (Tornatzky & Fleischer, 1990). Therefore, there are no uniform preferences and adoption rates within the HCV market expected, equal to the PC market.

3 Development of the market model framework

The adaptation of SD models from the PC to the HCV market is set in the context of the German market. Thereby we exemplarily focus on a conventional powertrain (e.g. Diesel), an alternative fuel powertrain (e.g. Liquefied Natural Gas), requiring a new independent refueling infrastructure, and a hybrid electric powertrain (HEV), not requiring additional filling stations. Thus, a HEV is not changing the user behavior, but as an emerging, innovative technology it has commonly agreed characteristics. As commercial vehicles are used for very diverse applications (Law et al., 2011), this initial study solely focuses on HCVs used for long-haulage applications, since they represent the highest share of new registered HCVs (Hill et al., 2011).

Table 1 – Overview of interviews conducted

Targeted stakeholder group	Contact with organizational representative of	Interviews	Other form of input	Content
Customers	Freight forwarders	7	-	Buying decision, decision process, preferences
HCV industry	OEM	-	Yes	-
	Automotive supplier	3	Yes	Market dynamics, technological input data
	HCV dealer	5	-	Market structure, buying decision, preferences
	Consultancy	-	Yes	Market dynamics, technological evaluation
Filling stations	Gas industry	1	Yes	Parameterization, general strategy, prices
	LNG station provider	2	-	Parameterization, general strategy, prices
Government	Government	-	Yes	Regulation, taxes & incentives

3.1 Stakeholder assessment

Secondary market studies, the theoretical framework for organizational adoption, and a qualitative primary study yielding to gather missing data for model parameterization are used to develop the market model. Thereby we have interviewed experts from the automotive industry, LNG providers, LNG filling station manufacturers, and long-haulage companies (cf. Table 1). As research design, semi-structured guided interviews and a selective content analytical transcription has been chosen (Luna-Reyes & Andersen, 2003).

There are several stakeholders, which are influencing the diffusion of alternative powertrain concepts on automobile markets. Albeit the stakeholders on HCV market are generally the same as on the PC market, their behavior patterns and objectives differ. Thus, we conducted a stakeholder analysis and evaluated the corresponding influencing factors for the diffusion process by a cross-impact study.

Customers are defined as freight forwarders using HCVs for long-haulage transportation. Although there is a huge variety of such companies – ranging from owner drivers to multinational companies – we cluster them in solely two different customer groups based on Roger’s Innovation Diffusion Theory: innovative and conservative companies (Rogers, 2003). Within these customer groups the firms are assumed having uniform as well as constant preferences and requirements. The investment decision upon a new HCV, and a powertrain concept respectively, is reached by an organizational process of the buying center according to the perceived technologies’ characteristics, the technology availability, and awareness. The rationality in decision making on B2B markets has been stressed. Furthermore, surveys revealed the most relevant criteria when buying a new commercial vehicle. Reliability, total cost of ownership and usefulness are among the highest ranked factors (Dressler et al., 2012; Kelp & Stolz, 2011; Diez & Krauss, 2006; Frost & Sullivan, 2010). Recently, image consideration also gains in importance, since B2B markets are generally driven by derived demand and therefore are still dependent on end-consumer preferences. Hence, the societal trend towards green, innovative, and sustainable transport solutions is conveyed through the entire supply chain.

HCV manufacturers (OEM) develop and offer commercial vehicles on the market. Due to simplification, the supplier industry is incorporated within this stakeholder group. Based on expected customer demand, governmental policies, and market trends, R&D expenditures are allocated for technology characteristics’ improvement and the expansion of a powertrain concept’s availability. Referring to Tornatzky and Fleischer, the availability is a decisive factor within the adoption decision process (Tornatzky & Fleischer, 1990). We define it as the variety of power classes which are available in different HCV models for the specific powertrain concept. Consequently, a low availability reduces the probability of a powertrain concept to be chosen by customers, because it could be ineligible to the customers’ transport task.

Refueling infrastructure incorporates managers of public filling stations. They decide upon their expected profitability whether they invest in alternative filling stations or not. Hence, the decision upon built-up or removal of filling stations is mainly influenced by a powertrain concepts’ stock in the market. However, many freight forwarders are using their on-site filling stations. In addition, freight forwarders are widely concluding contracts with a few of public filling stations spread over their general cruising radius. In doing so, bulk consumer prices for fuel are achieved and costs are reduced. In summary, considerably fewer filling stations per square kilometer are required compared to PC market. A spatial disaggregation of the refueling infrastructure, as shown in Struben (Struben, 2006), is not used in the model. Instead a homogenous distribution is assumed and the infrastructure is separated in urban and highway stations. For long-haulage trucks primarily highway stations are necessary for an unrestrained usage.

The Government sets market regulations, fuel and vehicle standards, taxes, and incentives. Despite the fact governmental decision making depends on market fleet GHG emissions or OEM lobbying attempts, modeling this as endogenous would led us out of scope of this article. Thus, governmental regulation is assumed to be exogenous. The influence of governmental regulation is implemented by policies measures as subsidies, taxes, and infrastructure development (Bosshardt, 2009; Zhang et al., 2011).

Besides the influencing factors of the stakeholder groups, there are further impacts. *Perceived technology characteristics* defines the attributes of a HCV powertrain concept, perceived by a customer buying a new vehicle. The development of technology characteristics doesn't underlie solely the OEMs' decisions but also general market rules, e.g. experience curves and economies of scale. Decisive factors for the organizational adoption decision are the technology availability (Tornatzky & Fleischer, 1990), total cost of ownership, purchasing price sensitivity and basically on an intra-organizational perspective the perceived usefulness, perceived ease of use (Frambach & Schillewaert, 2002), and image to achieve social desirability (Venkatesh & Davis, 2000; Johnston & Lewin, 1996; Frambach & Schillewaert, 2002). *External factors* are exogenous effects out of influence by the model behavior. In addition to the governmental regulation, primarily European fuel prices, the fuel consumption and the maximum improvement of technologies are regarded. *Minor relevant factors* could influence the HCV market dynamics, but are not assumed having a major impact. Thus, these factors are not used explicitly or are fully disregarded. Among them are interdependencies with the PC market, HCV drivers preferences or 2nd life car market (implicitly used), and biofuels, dealer consultancy, demographic change or urbanization among others (disregarded).

3.2 Model generation

In this section we discuss the adaptation of appropriate parts of PC SD models in order to establish a SD model for the HCV market. The aim of this model is to simulate the market shares of alternative powertrain concepts in new registered HCVs to analyze the future market penetration. Based on the four main feedback loops of powertrain diffusion patterns on automobile markets and the relevant stakeholders, the market model is developed. To assure the structural validity of the transferred model, we highlight the required changes to structure and parameterization of the original model parts, based on empirical and theoretical foundations. The dynamic hypothesis of the SD model resulting from the four main feedback loops and the system analysis is stated by the generalized causal loop diagram shown in Figure 1.

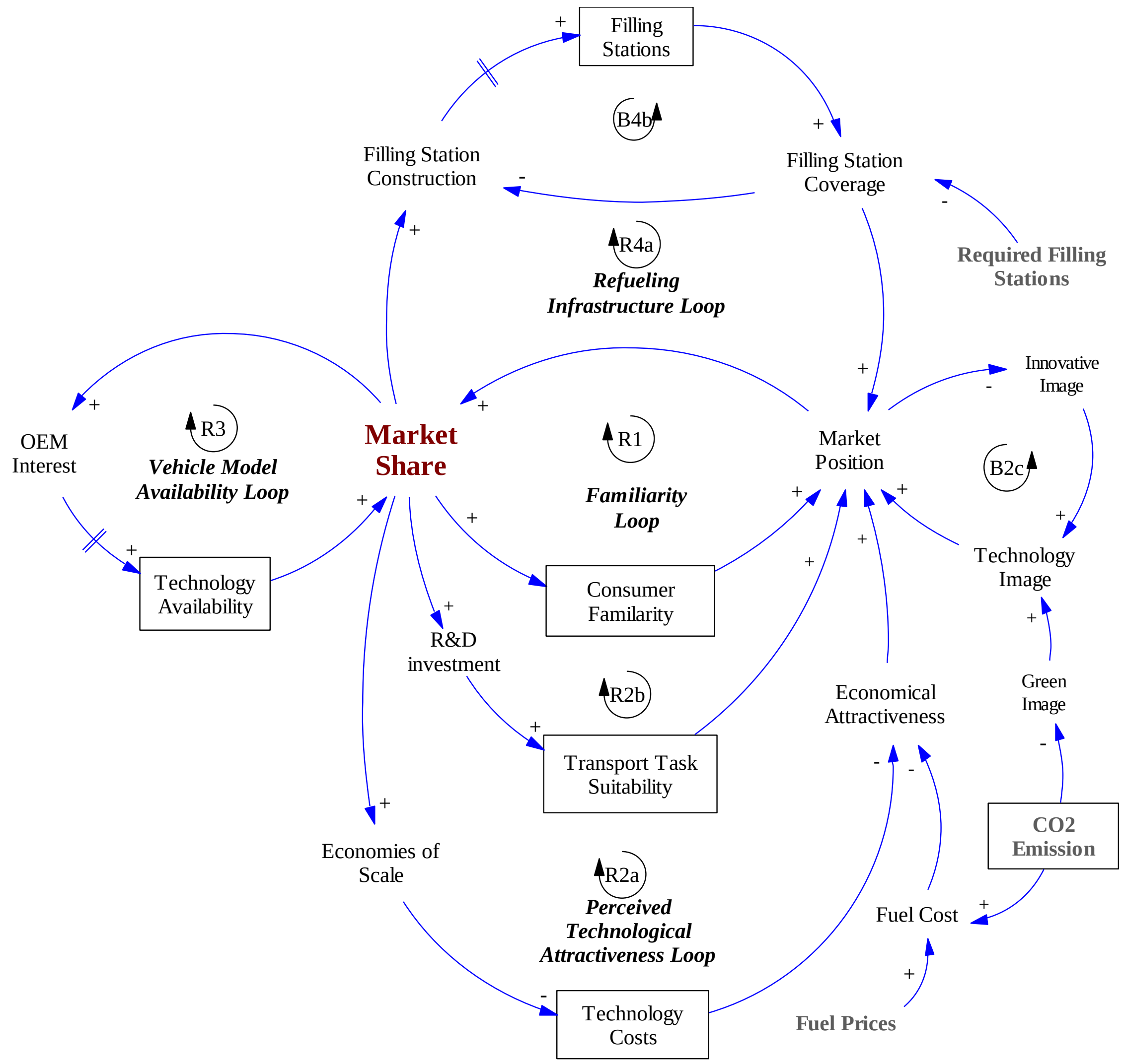
Organizational buying decision module

The market share of a powertrain concept is calculated based on a buying decision model using a utility choice model, similar for instance by Struben (Struben, 2006) or Weikl (Weikl, 2010). Regarding the organizational buying, we don't focus on the intra-group processes of the decision making unit. For simplification we do rather assume all people involved in the organizational buying process decide upon one combined decision rule. Therefore, the market share of the conventional as well as the alternative powertrain concepts is a function of an organization's familiarity with it, the perceived technological attractiveness, and the vehicle availability.

Furthermore, due to the rationality on B2B markets, we assume organizations judge product options fully independent of the product option currently in use. Additionally, there is no observable error of organizations, when evaluating a product option. Hence, the market share of a technology is directly derived by the probability an organization is choosing a certain powertrain concept. Consequently, the market share calculation is not based on the bass diffusion model; instead we are using a utility choice model. Therefore, we use the Bradley Terry Luce decision rule (Green & Krieger, 1988). If an error part in the utility evaluation of the organizational buying center is assumed, a multinomial logit model could be used (Struben, 2006; Keith, 2012).

Due to missing empirical studies on European freight forwarders' preferences when investing in a new truck, utility functions are approximated based on the Prospect Theory. Thereby, losses in attribute characteristics are judged higher then gains by the same extent (Kahneman & Tversky, 1979).

Figure 1 - Generalized Causal Loop Diagram



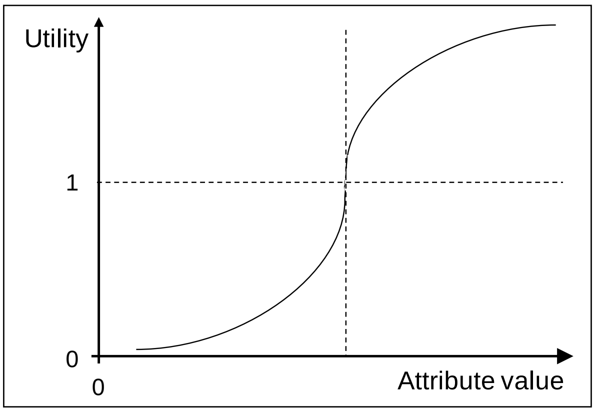
Peters et al. discussed the application of the Prospect Theory for automotive markets (Peters et al., 2008). Each utility function is parameterized with a reference utility of 1, based on current costs and preferences of freight forwarders in Germany (cf. figure 2).

The decomposed attribute utilities *A* of the perceived technological attractiveness (Figure 3) are aggregated to the total utility *U* using a polynomial non-compensatory decision rule with the attribute coefficient β. To sum up, we define the probability *p* at time *t* an organization *i* is choosing a product option *j* under familiarity *F* and availability *O* by:

$$p_{ij}(t) = \left(\frac{U_{ij}(t)}{\sum_{m \in j} U_{ij}^{m}(t)} \right) \times O_{ij}(t) \times F_{ij}(t) \qquad (1)$$

with $$U_{ij}(t) = \prod^{k} A_{ij}^{k}(t)^{\beta_k} \qquad (2)$$

Figure 2 - Prospect Theory: utility function

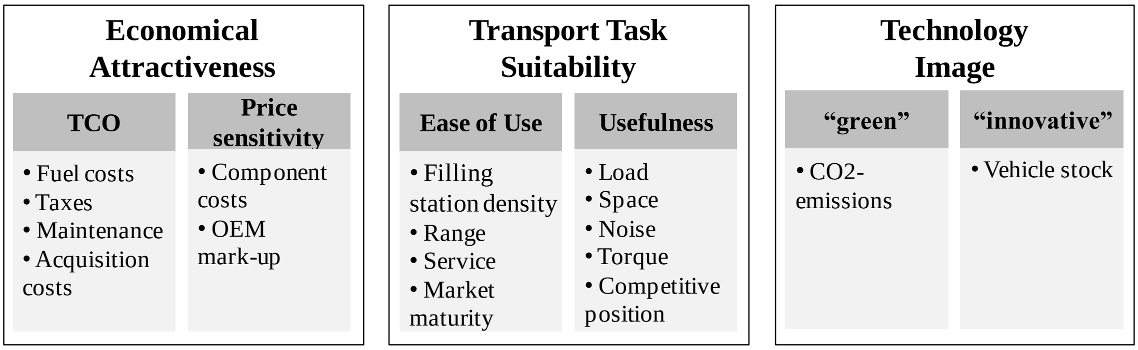


Perceived technological attractiveness loop

Based on customer requirements, the perceived technological attractiveness is determined by the economical attractiveness, the suitability to the transport task and the technology image (Figure 3). The modeling of this feedback loop is partly similar to models for PC market. The structure is slightly adopted in order to account for HCV customer specific requirements; in contrast the parameterization is particularly different. Technology data is mainly derived from secondary studies (Law et al., 2011; Hill et al., 2011) and expert interviews. Referring to Weikl, we implement the technological attractiveness endogenously (Weikl, 2010). The customer preferences represent the major difference between the PC and HCV market. OEMs as the supply side of the market are assumed to act on both markets identical. This means technological and economical progress of the powertrain concepts in the HCV industry follows the same functional rules as in the PC industry.

Initially, alternative powertrain concepts have a reduced attractiveness due to lower transport task suitability, caused by additional installation space and load, the immature technology, and missing filling and service infrastructure. The filling station coverage is given by the infrastructure development loop.

Figure 3 – Decomposition of the perceived technological attractiveness



The remaining factors of the transport task suitability are improving with increasing market share, due to experiences and higher R&D expenditures. This functional relationship is implemented by a S-shaped increase of the different transport suitability factors. At the beginning, experiences and expenditures remain limited caused by low market share *S*. After a certain market penetration the technological improvement rises until the transport task suitability *TS* reaches asymptomatically the technological maximum. Generalized, the mathematical formulation of the improvement rate *i* at time *t* reads as follows:

$$i(TS(t), S(t)) = \left(1 - TS(t)\right) \times S(t) \qquad (3)$$

The structure of the economical attractiveness loop is transferred widely unchanged from PC market. It is given by the acquisition costs of a powertrain concept and the expected total cost of ownership (TCO). According to the learning curves concept, economies of scale reduce the fixed cost (Sterman, 2000; Weikl, 2010). The variable costs are implemented as exogenous input by constant governmental regulation and the exogenous improvement of fuel consumption.

The relevance of image consideration is increasing within the HCV industry. On the one hand, "Green Logistics" gets a crucial decision factor in the transportation sector (McKinnon & Piecyk, 2009; Dressler et al., 2012; Klink et al., 2010). On the other hand, Rogers mentioned image as one core construct in his Innovation Diffusion Theory, similarly to Johnston and Lewin for organizational buying in general (Rogers, 2003; Johnston & Lewin, 1996). Thus, the technology image is defined by an innovative image, determined by the market share, and a green image, determined by the CO_2 emissions. Furthermore, the perceived technology image is also dependent, whether a company is innovative or conservative.

Familiarity loop

Familiarity does not solely play a role for individuals but for organizations as well. Drivers of HCVs share their experiences of trucks among themselves and convey knowledge about new powertrain concepts into the organization. Managers of transportation companies broaden their know-how by visiting exhibitions or consulting of HCV salesmen. Thus, word-of-mouth and advertising are a factor for the adoption of alternative powertrain concepts by forming the consideration set and levering the observability (Frambach & Schillewaert, 2002).

Struben defined familiarity as the "cognitive and emotional process through which drivers gain enough information about, understanding of, and emotional attachment to a platform for it to enter their consideration set" (Struben, 2006). For the diffusion of alternative powertrain concepts we transfer Struben's model from PC market widely unchanged to the HCV market to consider the effect of marketing and promotion efforts as well as word-of-mouth. We extend the model by implementing the two different B2B customer groups: innovative and conservative companies. Innovative companies are less risk-averse and are actively seeking for new technologies improving their business performance. Consequently, their familiarity rises faster than within conservative ones. Compared to passenger cars, social expenditures between members of transportation firms are more rare then between private persons, which is regarded by an adapted parameterization.

Refueling infrastructure loop

Based on an evaluation of different modeling approaches for refueling infrastructure development, we implemented this loop according to the model of Janssen (Janssen, 2005). A spatial disaggregation of the infrastructure as by Struben is not considered (Struben, 2006). Routes of HCVs are principally more predetermined than those of PCs. A spatial disaggregation of the refueling infrastructure would require very detailed information about transport flows. The simplified approach of Weikl (Weikl, 2010) doesn't seem to be appropriate, since the filling station (FS) density is assumed to have major importance for the diffusion of alternative fuel HCVs. The approach of Janssen (Janssen, 2005) and Keles & Wietschel (Keles et al., 2008) are similar, however, Janssen's work is preferred due to the simplified replicability. Nevertheless, the idea of Keles & Wietschel about separating the refueling infrastructure into urban and highway filling stations is implemented. Companies in transport sector use - in contrast to private passenger cars – company-owned on-site filling stations and contracts with public filling stations. Thus, it is assumed fewer public filling stations are required in order to achieve a satisfying coverage. Additionally, we solely consider highway filling stations, since those are predominantly important for long-haulage HCVs. Nonetheless, there exists a central uncertainty about the number of filling stations required for a satisfying coverage for the HCV customers. By developing different scenarios, this issue is regarded in the upcoming section.

The adoption parameters for the Bass Diffusion model of the filling station managers are assumed to be similar to PC market (Janssen, 2005). However, the parameters for profitability are adjusted according to secondary studies and expert interviews.

Vehicle model availability loop

The interest of an OEM for a powertrain concept *j* depends on the societal and economical pressures on the OEM to innovate. The economical pressure is determined by the actual market share *S* and the awareness of technologies to customer, perceived by the OEM Market Research *R*. The societal pressure is explained by the average change of ecological awareness *E* and the political will for GHG emission reduction. Based on the assumption PC OEM are acting according to comparable decision rules as HCV OEM, the OEM interest *O* is explained similar to Weikl, incorporating the HCV market specificities (Weikl, 2010).

$$O'_j(t) = \left(1 - O_j(t)\right) \times \left((S_j(t) + E_i(t) + R_{ij}(t) + \right) \times \delta^{,CO2\,Attr}(t) \qquad (4)$$

Finally, the vehicle model availability is directly derived by the interest of the OEM, delayed by the development time for new powertrain concepts and model generations of the OEM (Weikl, 2010; Sterman, 2000).

4 Discussion of the simulation model

The SD model is implemented based on the market model framework. By using an exemplary Base Case, the structural validity of this model is discussed, the model generated dynamics are analyzed and the most sensitive parameters are highlighted. The parameterization of the Base Case corresponds to the referenced models, if not otherwise stated. The HCV market specific parameters are provided in Table 2.

Table 2 - Parameterization Base Case

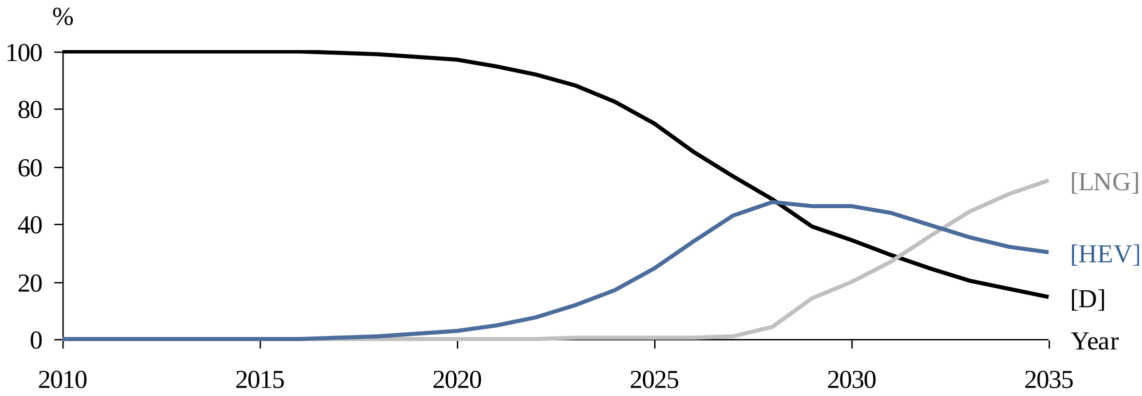
Loop	Variable	Value			Source / Comment
Infrastructure	Required FS density [Dmnl]	10%			Assumption based on expert interviews
	Interval proactive FS managers [year]	[SOP – 2025]			Assumption based on expert interviews
	Standard gross margin on LNG [€]	0,05			Calculation based on expert interviews
	FS investment cost [T€]	500			Expert interviews
	Number of highway fuel stations [FS]	350			For Germany, source: Tank & Rast, Energie Informationsdienst, CESifo-Gruppe
	Governmental FS program [FS/year]	2			Expert interviews, project LNG Blue corridor 2015 – 2020
OEM		**D**	**HEV**	**LNG**	
	Start of Production (SOP) [year]	-	2016	2018	Expert interviews
	OEM mark-up [Dmnl]	50%	50 %	50%	Profit margin of OEM on unit costs
Technology	Engine noise [0;10]	8	9	10	Expert judgments, noise as a potential restriction
	Add. load [kg]	-	+350	+300	TIAX (2011) & expert judgements
	Add. installation space [Dmnl]	10	8,5	9	Expert judgments & TIAX (2011)
	Power / torque [Dmnl]	9	9,5	8	LNG: lower torque, HEV: e-Engine for peak-power
	Tank volume [ltr] / [kg]	720	720	200	Expert interviews
	Avg. fuel consumption 2020 [ltr] / [kg]	31 ltr	29 ltr	26 kg	AEA (2011) & expert interviews, HEV: 6% fuel efficiency
	Unit costs 2020 [T€]	17	24,5	30	Expert interviews, no additional resale value for LNG & HEV
	Learning rate [Dmnl]	-1%	-12%	-10%	Cost reduction in percent by doubling of production volume
	Fuel price 2035 [€/l] / [€/kg]	2,34	2,34	1,67	Expert interviews and extrapolation 2025 – 2030 to 2035
Customers	Period of usage [year]	4			Expert interviews
	Interest rate	10%			Avg. capital costs, expert interviews
	Effective contact rate user / non-user	10% / 5%			Own assumption: Less B2B contacts than private contacts
	Risk aversion conservative companies	10% - 0%			Decreasing with increasing market share Rogers (2003)
	Marketing effectiveness	20 %			Proactive information gathering of B2B customers, referring to FS manager marketing effectiveness of Janssen (2005)

4.1 Structural validity

Regarding the structural validity of the simulation model it can be stated so far: based on validated SD simulation models for the automotive market aiming to forecast the market penetration of alternative powertrain concepts in passenger cars a market model for the same purpose for HCV has been derived. By evaluating existing models, those model parts fitting best to the problem at hand were identified. Nonetheless, the differences of both markets have been highlighted by using empirical and theoretical findings. These differences are considered by structural changes and an adjusted parameterization. Thus, the model should represent – to certain extent as a heuristic – the real system. Additionally, a dimensional consistency test has been performed successfully. To sum up it can be stated, the model passes the direct structure test (Barlas, 1996).

Besides the direct structure tests, there are structure-oriented behavior tests for evaluating the structural validity. Thereby we use extreme-condition and behavior sensitivity tests (Barlas, 1996). Moreover, we analyze the dynamic behavior of crucial feedback loops. With the given structure and parameterization we simulated a Base Case of the market share development for the three powertrain concepts: conventional Diesel engine powered truck [D], Diesel hybrid electric truck [HEV], and a monovalent liquefied natural gas truck [LNG] (Figure 4).

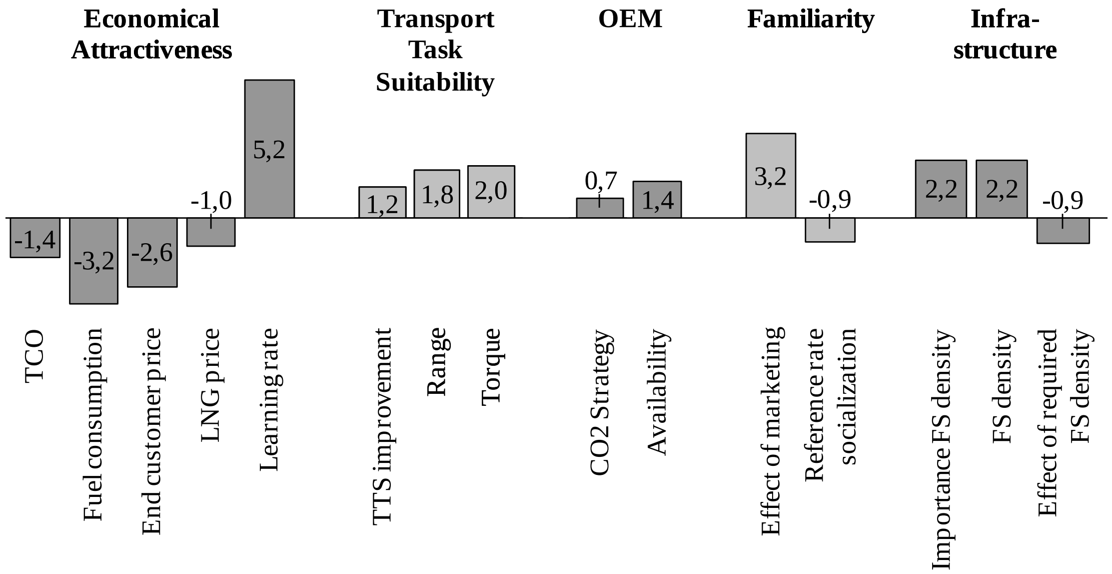
Figure 4 - Base Case simulation



The simulation of the Base Case shows that the diffusion of the HEV is starting right after the start of production (SOP) in year 2016. Due to lower TCO and a green innovative image, at first Innovators and later on Mainstream buyers start adopting this new technology. With increasing market penetration the transport task suitability improves and the customers get more and more familiar with this technology. The successful diffusion process gets interrupted by a strong and fast market penetration of the LNG. After the SOP in 2018 it takes roughly 10 years until LNG reaches a noticeable market share. Despite marketing efforts and a governmental LNG station program, the filling station density remains lower than needed. With an increasing economical attractiveness and familiarity, suddenly a tipping point is reached and a self-sustaining process of infrastructure built-up, transport task suitability improvement and increasing familiarity starts. As a result, the diffusion of the HEV fails to certain extent and LNG would get the most widely used technology. Consequently, the conventional Diesel engine would get a niche application towards 2035.

Based on this Base Case simulation, in the following we highlight those parameters to which the model is highly sensitive and discuss whether this behavior could fit to the real system. Additionally, we evaluate the impact of uncertain parameterization. Therefore, we increase all parameters by 1% and compare the average relative effect on the market share of LNG for the years 2020, 2025, 2030, and 2035. Figure 5 shows the most sensitive parameters of each feedback loop.

Figure 5 - Most sensitive parameters on LNG market share 2035 by module [%]



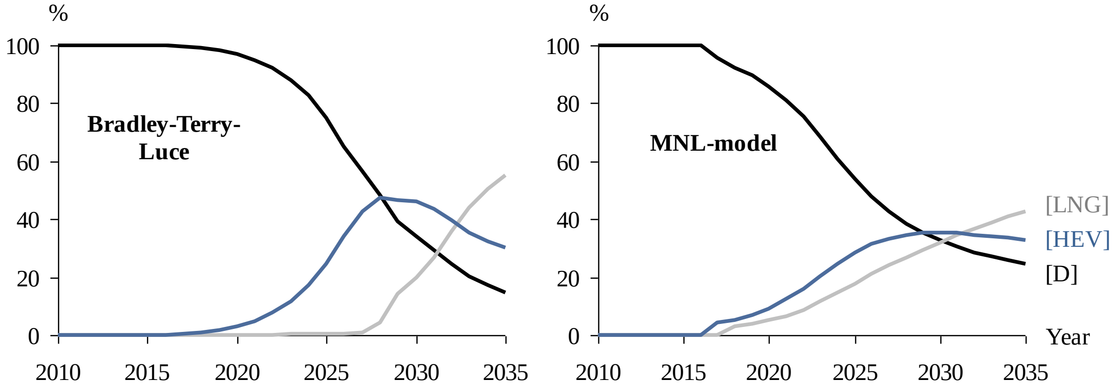
The exponential effect of the learning rate in decreasing costs of alternative powertrain concepts has a major impact on the market share development. The relevant buying criteria for freight forwarders have a significant influence as well, according to the sensitivity of costs, fuel consumption, and transport task suitability. Likewise, the sensitivity of the infrastructure loop highlights the particular importance of the filling station density. The marketing effectiveness has a significant impact on the familiarity loop, whereas the effective contact rate between users and non-users has a minor influence. On the one hand, this fits to the parameterization derived by theory and studies but contradicts partially some expert interviews. Thus, a future refinement of the familiarity loop by using empirical insights is advisable.

Varying a parameter by 1% provides a static sensitivity analysis, since it solely evaluates the effect in an incrementally changed market environment. Dynamic or disruptive changes can't – and shouldn't – be expected. Therefore, we take up the results of the HCV market system analysis and evaluate whether effects cause an intended or unintended disruptive model change. Consequently, we discuss the following hypotheses:

H1: Using a MNL buying decision model will not cause a disruptive model change.

The different methods to convey a customer's utility into the resulting market share are heuristics of the reality. Nevertheless, the decision rules shouldn't cause a disruptive model change. The comparison between the Base Case with the Bradley-Terry-Luce utility choice model and a MNL-model reveals similar behavior and trends of the market share development. However, using MNL the market penetration of LNG starts immediately after the SOP caused by the compensatory choice model. Additionally, the unobservable part of the utility causes a lower total sensitivity of the model. To sum up, we suggest evaluating this issue by a thorough customer study, e.g. conjoint analysis, to determine the choice model empirically. Nonetheless, the general meaningfulness of the model remains.

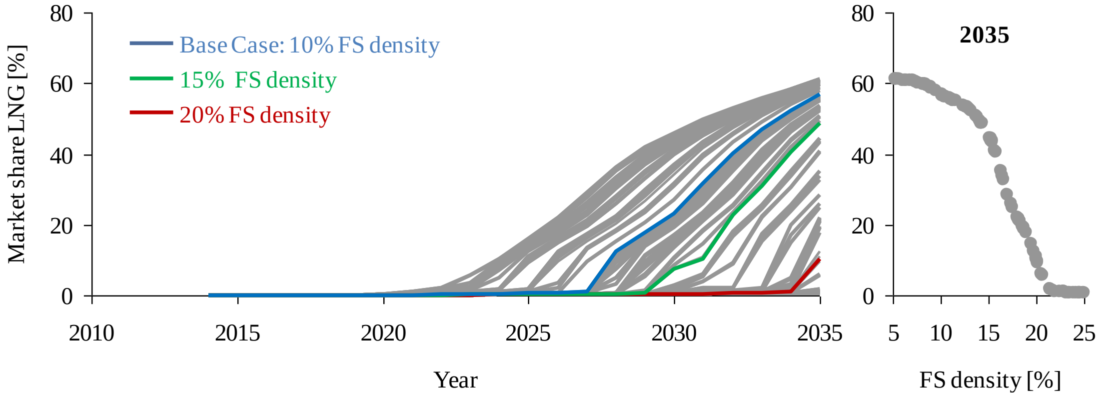
Figure 6 - Base Case simulation with Bradley-Terry-Luce (left) vs. MNL-model (right)



H2: A high required station density will prevent LNG from market diffusion

In order to test this hypothesis we conduct a Monte Carlo simulation of the Base Case with varying the parameter *required FS density* using a normal distribution with μ = 10% and σ = 5%. The individual traces show, this parameters prevent the diffusion of the LNG significantly. The plot of the LNG market share depending on *required FS density* shows the functional relationship on the LNG market share in 2035. Therefore, the hypothesis is corroborated. However, it shows the outstanding influence of this parameter and highlights the importance of a valid and empirically derived value.

Figure 7 - Monte Carlo Simulation of the LNG market share (left) and results plot for the year 2035 depending on the parameter *required FS density* (right)



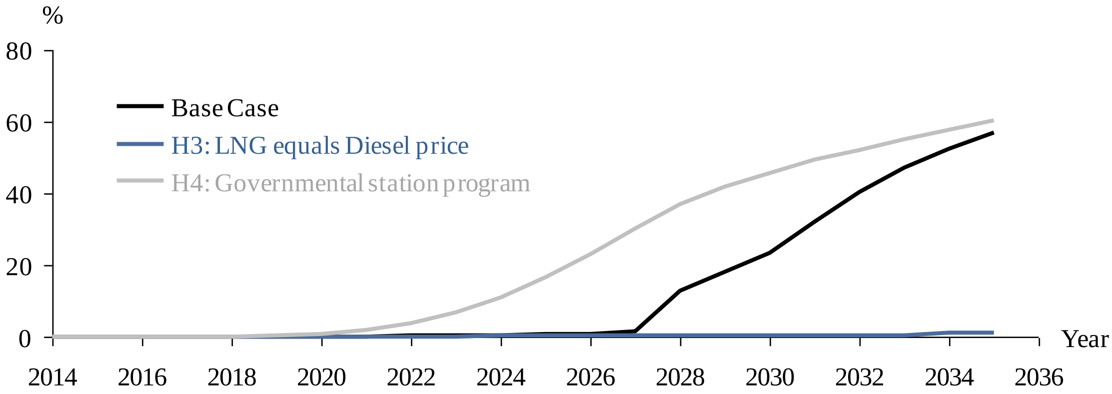
H3: If LNG fuel costs equal the costs for Diesel, the LNG powertrain concept will not penetrate the market

Referring to Figure 8 we corroborate this hypothesis. The major benefit of the LNG powertrain concept of substantially lower fuel costs doesn't exist anymore. Due to higher acquisition costs and lower transport task suitability, the diffusion of this powertrain concept would fail.

H4: A focused governmental filling station program with 50 operating filling stations towards 2020 will push the diffusion of the LNG powertrain concept

Towards 2035, the increased governmental station program solely has minor influence on the LNG market share. In contrast, the diffusion starts right after the SOP, since the transport task suitability is not reduced by missing refueling infrastructure. Consequently, we corroborate this hypothesis. However, the lack of familiarity, availability, and disadvantageous attributes of the transport task suitability limit the market penetration in early years. Concluding the results of Figure 8 and Figure 7, a market saturation of the LNG powertrain concept of roughly 65% towards 2035 is recognizable in absence of an infrastructural constraint.

Figure 8 - Scenario simulation for H4 and H5



In summary, the sensitivity analysis and the disruptive parameterization changes reveal reasonable behavior patterns, which fit to the real system. Thus, the model passes the structure-oriented behavior test. Therefore, the transfer of existing SD models from the PC to the HCV market has been successful in terms of the structural validity. As a transient behavior model, Barlas suggests the "use of graphical and visual measures of typical behavior features" for behavior pattern tests (Barlas, 1996). Regarding the behavioral validity, the model shows correct patterns in terms of trends and general behavior in the Base Case parameterization. However, we have outlined factors, which are on the one hand highly sensitive and on the other hand highly uncertain due to missing empirical insights. Hence, we propose to judge the behavioral validity finally after more empirical data has been gathered on the HCV market.

4.2 Discussion of the model results

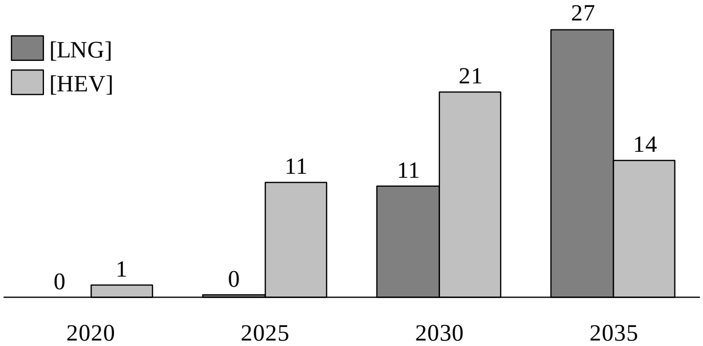
Despite the fact that the model hasn't conclusively passed the behavioral pattern test, we are confident in the general behavior. For this reason, we discuss the revealed interdependencies and outcome of the diffusion patterns of alternative powertrain concepts on the HCV market.

The Base Case simulation shows that hybridization of long-haulage trucks is a promising measure to reduce GHG emissions of the transportation system initially. Customers quickly adopt this new technology, due to TCO advantages, similar handling, and a green as well as innovative image. However, the HEV turns out as a transition technology towards a low carbon transportation system. In our case the LNG powertrain concept, but potentially other alternative fuel trucks as well, has significantly higher cost saving potential. Yet, these technologies require a new independent infrastructure and are fundamentally driven by its development. The network effect of the infrastructure development loop for long-haulage HCVs seems to be much more essential than on the PC market. On the one hand, a missing infrastructure hinders the usage of such HCVs; on the other hand, high annual mileage and fuel consumption offer a large as well as stable turn-over potential for LNG stations. With the given parameterization, for 2035 we prospect an annual LNG consumption in Germany of about 3 bn kg. Adducing a standard gross margin on LNG of 5 €Cent/kg, the profit potential amounts to over 150 m€ annually.

The investigation of hypothesis 4 shows, an initial satisfying German LNG infrastructure network of 50 stations could be achieved by investment costs of roughly 25 m€ (cf. Table 2). Therefore, we assume the largest lever for the diffusion of alternative LNG powertrain concepts by the refueling infrastructure development. In contrast, a subsidy for LNG trucks would not significantly influence the diffusion before the refueling infrastructure development has started. Nevertheless, increasing LNG taxes would hinder the LNG diffusion as hypothesis 3 reveals. In the case of HEV, a legislation to compensate for the additional load and a technology subsidy provides the most promising lever for the future market share.

By using the prospected market share of the Base Case simulation, we estimated the sales potential of alternative powertrain concepts in long-haulage HCVs in Germany. We assume a long-haulage truck share of 40 % (Hill et al., 2011) and sales forecasts for Germany based on a large automotive industry market information provider. Figure 9 shows estimates for the upcoming years and highlights the enormous market potential of alternative powertrain concepts. This could justify the manufacturer's investments in the development of these technologies. Furthermore, the average GHG emissions of the new registered long-haulage truck fleet would reduce from roughly 900 g/km per truck by 20% to 725 g/km in 2035. However, these numbers should solely provide a tendency towards 2035, due to some uncertain parameters.

Figure 9 - Sales potential of alternative powertrain concepts for long-haulage trucks in Germany [in thousands units per year]



To sum up, the model forecasts a substantial transition of the long-haulage truck market. Albeit we adduced LNG and HEV as exemplary powertrain concepts, the shift towards low carbon transportation could also be driven by other concepts. Synthetic fuels or fuel cells, for instance, could equally substitute the conventional Diesel powertrain. However, without a satisfying filling station density this transition will not take place. Particularly in early years, conservative transportation companies are skeptical towards new powertrain concepts. Marketing for the superior economical attractiveness and the deletion of transport task suitability restrictions by the OEMs are effective measures against the skepticism.

5 Conclusion and Outlook

The aim of this paper is to discuss the application of existing PC system dynamics models for analyzing the future market penetration of alternative powertrain concepts on the HCV market. Thereby we focused primarily on the structural model validity, in order to get a deeper understanding of the transition towards low carbon transportation and outline future fields of research. Summarizing, the model turns out to be structural valid as well as capable to study the fundamental market dynamics and highlight the sensitive factors of the diffusion process. Yet, there are several limitations due to missing empirical data and the comprising simplification caused by focusing solely on the German long-haulage HCV market.

Implications for practitioners (Stakeholders)

Governmental stakeholders have an outstanding influence on the adoption of alternative fuel trucks. By an external intervention for an immediate infrastructure built-up, the tipping point of the network effect could be reached soon. Especially compared to PC market, the effect of external infrastructure built-up is higher, as lower station density is sufficient for a satisfying coverage. Moreover, supervising the refueling infrastructure built-up could reduce the required FS density by an optimized location planning.

A large turn-over potential for LNG providers and filling stations is expectable, if a successful market penetration of LNG trucks would take place in Europe. Therefore, we suggest an analysis of the effect of this scenario on the energy supply system in terms of LNG availability, distribution, and prices.

Implications for researchers

The adaptation of SD models from existing markets to related markets facilitates the modeling process significantly: a basic understanding of the problem is gained much faster, collection of required data can be conducted more purposefully, and central hypotheses can be stated early in the modeling process. Nonetheless, a profound discussion of the structural validity by the change of structure and parameterization is required.

Moreover, future research for a more reliable and holistic understanding of the market penetration of alternative powertrain concepts in HCVs is needed. Qualitative and quantitative studies of the demand side of the HCV market are rare. Analyzing the organizational adoption behavior in more detail, determining empirically derived utility functions, and evaluating the required filling station density could contribute extensively to the understanding of diffusion processes of low carbon technologies in the freight transportation system and the behavioral validity of the SD model.

Additionally, we propose analyzing the diffusion of other powertrain concepts (e.g. fuel cell) and the influence of vehicle measures (e.g. aerodynamics, waste heat recovery) on those. Finally, a stepwise adoption of alternative powertrain concepts from urban, to regional, and international applications could be possible. Thus, other HCV use cases, such as regional distribution or urban applications (garbage, city bus, lower distribution) should be taken into account as well.

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