Karlsruhe Institute of Technology

Conceptual Causal Framework for the Diffusion of Emerging CO_2-saving Technologies in Heavy Commercial Vehicles

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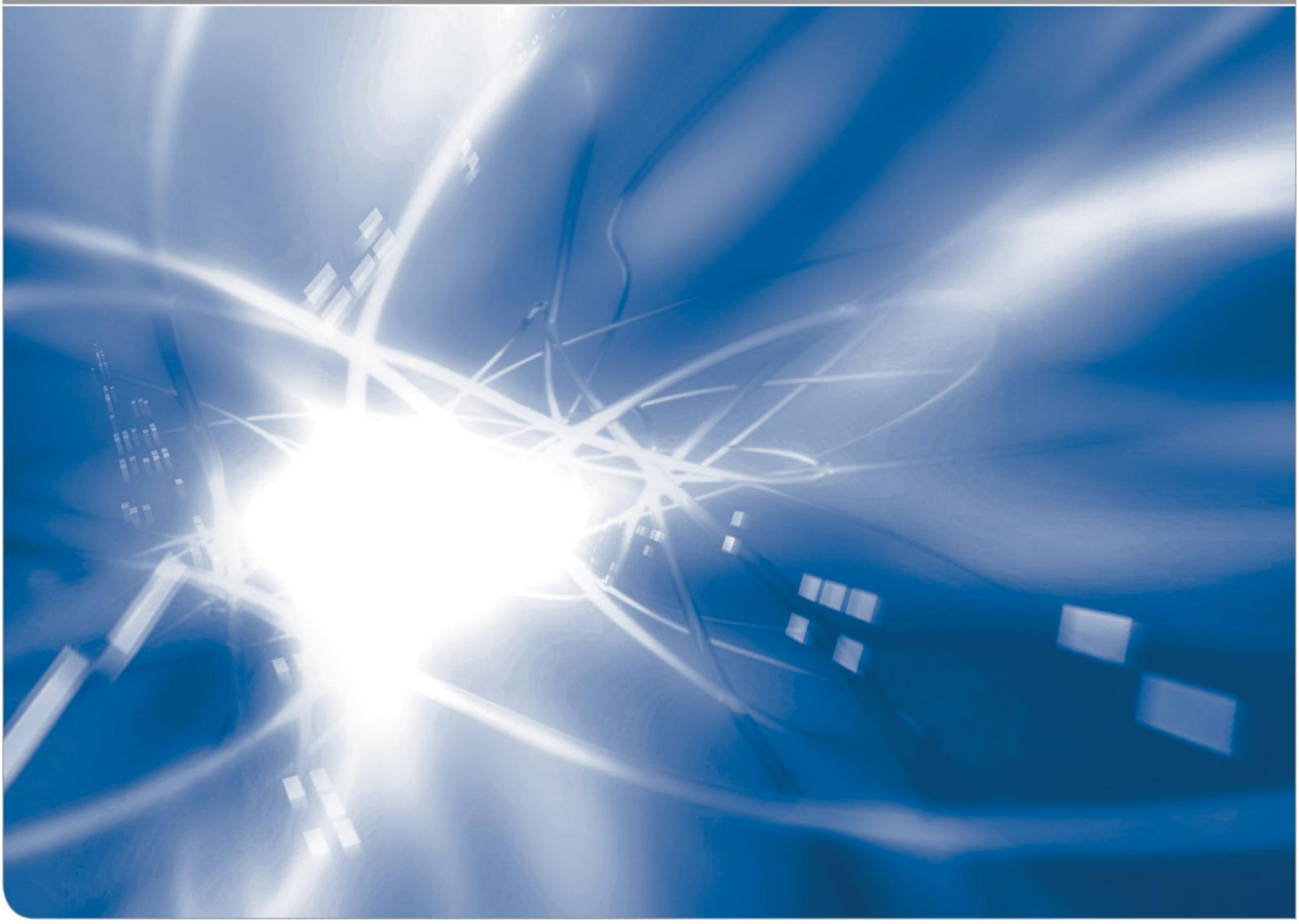

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This working paper has been developed, elaborated and written until December 2013. It formed partly the basis for a publication and presentation on the 32nd Conference of the System Dynamics Society 2014 [64].

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Impressum

Karlsruher Institut für Technologie (KIT)
www.kit.edu

2014

ISSN: 2194-1629

Abstract

Facing the targeted CO_2 emission reduction of the transportation system, market forecasts for CO_2 emission reducing technologies in heavy commercial vehicle (HCV) are needed. Compared to passenger car market, however, the HCV market is less analyzed due to the dissimilar market structure. Thus, this working paper proposes a conceptual causal framework for analyzing the future diffusion of technologies reducing CO_2 emissions in HCV. The framework incorporates existing studies about HCV markets, an overview of market forecasting methods, and the HCV specific setting of organizational adoption of innovations. The paper identifies the most influencing stakeholders, in particular truck manufacturer, HCV customer, energy supply system and government. The core interdependencies of different stakeholders are integrated into causal System Dynamics (SD) model. For future research this framework should be quantified, applied and validated on the European market.

Keywords:
System Dynamics, heavy commercial vehicles, technology diffusion, forecasting, CO_2 emissions

Content

1 Introduction

Commercial vehicles are the backbone of the European transportation industry. The road freight transport accounts for 75.5 % of the EU-27 tonne-kilometres [1]. 12 % of European anthropogenic CO_2 emissions were produced, while transporting goods and passengers with HCVs.

To reach a CO_2 reduction target of 60% for transport in 2050 compared to the base year of 1990, the European Commission will propose a strategy targeting fuel consumption and CO_2 emissions from heavy and medium commercial vehicles (HCV)[1] [1,2]. Additionally the truck industry announced a self-commitment to reduce the CO_2 emissions by 20% until 2020 [3].

To achieve these goals a significant increase in the variety of technologies reducing CO_2 emissions in HCV is expected [4]. This will bring root and branch changes to the world of transport: Companies in logistics, freight and public passenger transport, truck industry as well as governmental organization are affected: Various studies on passenger car market showed the importance of governmental policies to develop a service and filling station infrastructure; By 2020 80% of logistic companies are expected to see CO_2 emissions as a significant factor in logistical decision making [5].

Previous work about greenhouse gas (GHG) emissions of freight and public transportation is principally concerned with prospected emissions levels [6–8] as well as reduction policies [4]. The future market split of technologies and therefore fuel consumption of HCV and MCV is mainly assumed [6,8], determined by simplified qualitative methods [9], or total cost of ownerships calculations [4]. Findings of market forecasting studies on PC power train technologies haven't been applied yet. Albeit the selection decision of technologies in HCVs seems to be also driven by rational as well as emotional criteria.

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[1] In this working paper, passenger cars (PC), light commercial vehicles (LCV), medium commercial vehicles (MCV) and heavy commercial vehicles (HCV) are defined according to the standards of the European Union and ACEA. Long-haulage trucks are HCV which are used for long-distance on-road freight transport.

To support further analysis in this field of research, the objective of this paper is to propose a conceptual causal framework for a thorough analysis of market penetration of technologies reducing CO_2 emissions in HCVs at example of long-haulage trucks in Europe. On this basis crucial interdependencies of future market diffusion will be identified to provide a basis for further research.

Therefore this working paper summarizes the results of automotive market forecasting studies in general and HCV market analysis in particular, complemented by implications of the technology diffusion in a B2B context (Section 2). Next a conceptual framework is proposed to identify influencing factors on market penetration of technologies reducing CO_2 emissions in HCVs. In order to model and forecast the market, the interdependencies of factors are highlighted on a cross-impact study (Section 3). Finally recommendations and conclusions are drawn to provide a basis for further research in the field of

2 Market forecasting models for the transportation systems and implications for the HCV market

In order to analyze the market penetration of technologies reducing CO_2 emissions on the HCV market, findings and validated methods of the PC and LCV power train and fuel split prognosis will be transferred. Those insights are complemented by results of existing studies and data of the HCV market. Additionally the specifity of organizational adoption of innovations is regarded to cope with the business-to-business (B2B) industry structure of the HCV market.

Thus a review of existing HCV market studies summarizes the information about the object of study at hand. The main techniques in automotive market forecasting and their applications are reviewed as well as the methods' strengths and weaknesses are outlined. Complemented by basic concepts of the organizational adoption behavior, an appropriate method for HCV market split forecasting is chosen.

2.1 HCV market analyses and forecasting studies

Compared to PC market, analyses and forecasting on the HCV market are rare. The market penetration of alternative power trains or low carbon emission concepts is even less discussed in research. This lack of attention might be corresponding to the comparison of fuel consumption reduction on both markets. The average CO_2 emissions of new registered PCs have dropped by 23% since 2000 [10]. Until 2020, a long term target is set by the European Commission of 95 g CO_2/km, which stands for a total 45% reduction compared to 2000. In contrast, the average CO_2 Emissions of long-haulage trucks haven't changed significantly within this period. A main reason is the Euro norm emission legislation, which caused the integration of fuel increasing exhaust gas treatment measures [9,11–13]. By 2014, the actual last emission standard EURO 6 is mandatory for all new registered trucks with a gross vehicle weight (GVW) of over 3.500 kg. Therefore the reduction of fuel consumption is expected to gain further in importance, as the European Commission will propose a strategy targeting fuel consumption and the ACEA shaped a self-agreement. To this extend various studies have been conducted to project GHG emissions of HCV based on assumptions about the future fuel consumption [14].

In general, there exist several options for the decarbonisation of the transport sector: Optimization of the supply chain, the change of modal split, technical measures and cruise management. Numerous studies discussed the potentials in supply chain optimization [15,16] and the change of modal split [17]. Technical measures can be clustered in internal power train improvement, use of power train peripheral technologies, vehicle measures and other energy sources [4,18].

A few studies discussing the future market penetration of these technological measures reducing CO_2 emissions of HCV in Europe. Shell issued a Goods Vehicle Study 2030 to analyze the long-term HCV market development. Their scenario analysis assessed an average technical fuel reduction of 16% to 21% by 2030 to HCV. Thereby, engine and transmission measures (10%), hybridization (2% to 5%) and rolling friction and air drag reduction (5% to 10%) are considered [9].

AEA (2011) provided an evaluation of technological options for reducing energy consumption and GHG emissions from HCV. It was shown, the market penetration differs significantly among various use cases. It was distinguished between Service & Urban Distribution, Municipal Utility, Regional Distribution, Long Haul as well as Coaches and City Busses. Key influence on the scenario analysis has been the expected payback time of the measures. Furthermore adequate policy instruments to drive the diffusion of technologies reducing CO_2 emissions are identified [4].

TIAX (2011) has analyzed the GHG reduction potential for HCV and assessed cost-benefit data to the reducing technological measures [19]. On this basis CE Delft has identified the technological, institutional and financial barriers to the implementation of technologies that improve fuel efficiency in the European road freight transport sector. Additionally, customer insights about their requirements and barriers for HCV efficiency measures have been conducted in a non-representative questionnaire [18]. In a second study CE Delft evaluated the potential of local zero emission trucks in the transportations tasks of distribution and long-haulage freight transportation. For long-haulage applications, fuel cell vehicles seem to be most appropriate measure in a long-term perspective. Battery hybrid vehicles are seen as a transitional technology from internal combustion engines to pure-electric power trains. The scenarios towards a transition of zero emission driving are based on a 'what-if" analysis and are not based through a logic model [6].

In an use-case specific setting as well, Tzeng et al. focused their alternative fuel analysis on inner-city public buses. They apply a multi-attribute evaluation process for hybrid, electric, fuel cell and methanol driven buses with criterion functions of costs, emissions and vehicle capability. In a short- and midterm perspective, hybrid electric buses tend to be the most suitable powertrain concept for this transportation task. If the cruising distance of electric buses increase, the pure electric bus could be the best alternative among the existing concepts [20].

The studies surveyed have all in common the future share of fuel consumption reduction technologies is based on qualitative methods or estimates. Quantifying methods have not yet been applied, which differs for a few studies dealing with the total market volume of commercial vehicles and some studies providing insights about general drivers of HCV market development. Diez (1983) has analyzed the influencing factors on total sales of HCV in Germany. The cyclic demand of HCV is mostly driven by the expected need for transportation services, the economic growth, ways of funding as well as fiscal and transport policy measures [21].

Based on econometrical and scenario analysis, the total demand for HCV was forecasted for Germany [22] and China [23]. Zhang showed how the drivers for total HCV sales in China differ between light, medium and heavy segment. Especially infrastructure concerns are an additional driver in an emerging market like China.

Furthermore there are several studies of various management consultancies discussing the total market development, the future technological market split and existing customer needs on the HCV market. The results confirm the previous presented insights. Additionally customer requirements were collected [24,25], OEM challenges outlined [26,27] and future technology shares estimated [25,28]. However, the methodologies and data collection methods aren't discussed based on scientific publication guidelines. Thus, the results cannot be used explicitly. Instead, they could support assumptions for the model implementation in case of insufficient empirical data.

2.2 Automotive market forecasting methods

Combining the findings in Shafiei (2013) and Al-Alawi (2013) there are four main approaches to cluster automotive market forecasting models: macroeconomic focused Top-Down approaches (System Dynamics), microeconomic focused Bottom-Up approaches (Agent-based modeling and Discrete Choice Analysis) as well as diffusion and time series models. Additionally, there are further, more practice-oriented, qualitative and quantitative approaches (Delphi method, cost-benefit-analysis, scenario analysis among others) [29,30].

Agent based modeling (ABM) is a simulation method using individual micro-level decision making entities called agents. Each agent acts based on the system it represents, its internal characteristics and the relationship to other agents [31–33]. This bottom-up approach has been used in many automotive market forecasting models, where agents represent key actors on the market: Original Equipment Manufacturer (OEM), various customer groups, fuel suppliers and policymakers. The application of ABM on automotive markets is exclusively limited to PC and LD markets – to the best of the authors' knowledge. For a comprehensive overview of ABM application on those markets please refer to Al-Alawi and Shafiei.

The application of ABM has shown its strength in simulating the individual agents' behavior and interactions in the environment. Hence, ABM can capture the heterogeneity of individuals within the market. In contrast, agent-based models are more difficult to calibrate, verify and validate as well as connected with higher computational costs [29,30].

System Dynamics (SD) is a modeling method for analyzing complex and dynamic problems as well as their structures in a socio-economic environment [34]. In market forecasting applications it is utilized as a top-down approach looking at the process of market development as a whole and facilitating to understand the interdependencies of various stakeholders in complex systems [30]. Again the application of the method is limited to PC and LD markets. SD as a top-down approach is used extensively as a decision support system for policy makers in public and corporate sector [35–38] Lyneis, [39]. Please refer to [30] for a more detailed review of SD models on automotive markets.

The strength of SD lies in providing a method for understanding automotive market and industry behavior as a whole by merging various, partially opposed, knowledge sources.

Thereby no huge databases or time series are required and qualitative structural market interdependencies can be modeled. This supports scenario analysis for decision and policy making. As a result, SD models are partially based on parameters being difficult to quantify. Additionally the aggregated modeling of complex problems is more suitable for qualitative predictions than precisely accurate forecasts [30,38,40].

Diffusion and time series models (DTSM) are based on the *Diffusion of Innovation* theory (DOI). It describes the reason, the process and the rate how new products or ideas spread into a market. The process of adoption or rejection of an innovation by an individual is determined by the innovation itself, the communication of (potential) adopters, time and the social system around [41]. The Bass model is one of the most widely used DTSM for the innovation diffusion in automotive markets [29]. Therefore the adoption rate and the corresponding time frame of the market development of new vehicles are estimated.

If sales data for new vehicle concepts exist, the parameters of the Bass model can be regressed, if not, analogs or surveys must be used to determine consumer's product adoption characteristics. As the future adoption can easily be estimated by historical trends or similar technologies, the DTSM is relatively simple to implement. However, the parameter approximation of other technologies is critical and few is known about pattern of innovations that failed. Also, these methods are not appropriate for forecasting the diffusion on markets with competing products [29].

Discrete Choice Modeling (DCM) is a method to describe and estimate choices of decision makers (individuals, households or decision making units) among a finite set of alternatives. Based on a choice set of alternatives being exhaustive and mutually exclusive the probability is calculated the decision maker chooses a particular alternative. On automotive markets, the DCM is primarily implemented as a multinomial choice with three or more alternatives assuming correlation (Nested Logit) or no correlation (Multinomial logit, conditional logit) among the alternatives [42]. A comprehensive description of this method can be found in Train [43] or Bierlaire [44], a review of key discrete choice models in [29].

If rich historical dataset of decision makers' preferences are available, DCM is beneficial to model their future choices. Additionally DCM provides transparent and valid statistical framework for consumer decisions. In absence of the historical datasets in turn, the decision makers preferences have to be derived from hypothesis or quantitative or qualitative

Author	Year	Methodology					Scope			Technologies						
		SD	ABM	DCM	DTSM	others	PC	LCV	HCV	conven. ICE	EV	Hybrid	Gas	FCV	Bio-fuels	Vehicle optim.
AEA	2011					x			x	x						x
Al-Alawi	2013	x	x	x		x	x			x	x	x				
Armenia et. Al	2010	x					x			x						
Bandivadekar	2008					x	x	x		x	x	x	x	x	x	
Bosshardt	2009	x					x			x	(x)	x	x	x		
Bosshardt et al.	2008	x					x			x		x	x			
Cahill	2002	x					x			x	x	x		x		
CE Delft	2013					x				x	x	x		x		
de Haan et al.	2009		x				x									
Eppstein	2011		x				x			x		x				
Ganesh	2010		x				x					x				
Janssen	2004	x					x			x		x	x	x		
Janssen, Lienin, Gassmann	2006	x					x			x			x			
Keles et al.	2008	x					x			x				x		
Kieckhäfer et al.	2012	x	x	x			x			x	x	x				
Kortelainen & Lättilä	2009	x	x													
Macal	2010	x	x													
Metcalf	2001	x					x			x	x	x		x		
Park et al.	2011	x					x			x		x		x		
Santa-Eulalia et al.	2011	x					x				x					
Schneider et al.	2003	x					x							x		
Shafiei	2012	x	x	x			x			x				x		
Shafiei et al.	2012		x				x	x		x	x	x	x	x	x	
Shell	2010					x			x	x						x
Sheperd et al.	2012						x			x	x	x				
Struben	2006	x		x	x		x									
Struben & Sterman	2007	x		x			x			x		x		x		
Supple	2007	x					x			x				x		
TIAX	2011					x			x	x						x
Tzeng et al	2005					x			x	x	x	x		x		
Vliet et al.	2010		x				x			x					x	
Wansart & Schnieder	2010									x	x					
Weikl	2010	x					x			x	x	x	x			
Zhang et al.	2011		x	x			x									

Figure - 1 Litearture review on automotive market models

customer research [29]. Also, customer decisions and changing market situations are barely taken into account.

Figure 1 gives an overview of key studies forecasting the market shares on automotive markets of technologies reducing GHG emissions. To meet problem specific solutions and deal with the single methods specific advantages and disadvantages, the methods discussed previously are widely combined. Especially DCM supports ABM and SD models to represent the consumer decision rules [30,35–38,40,45]. Additionally, primarily SD models are complemented by the DOI to account for different adopter categories and principle technology diffusion patterns [35,38,46,47]. Recent research streams indicate, hybrid SD-ABM is a promising approach as well [30,37].

Summarizing it can be stated, System Dynamics offers a flexible framework for modeling general market dynamics and incorporating other methods' advantages in the same time in order to cope with its own limitations partially.

2.3 Organizational adoption and buying on automotive markets

The majority of forecasting studies on the automotive market are based in a setting of individual adoption of innovations, since the PC market follows business-to-customer (B2C) market characteristics: In Europe 40% of new registered PC are bought by private persons and 60% by companies. Nevertheless roughly just 35% of new registrations on companies are completely independent of the driver's decision [48,49].

This differs significantly for the HCV market. Commercial vehicles are – as the name implies – in general used for commercial purposes. Thus, the market where commercial vehicles are supplied and demanded underlies the characteristics of a B2B industry. Purchasers of commercial vehicles are businesses themselves that use HCV as production factors to produce products and services for their customers.

The adoption and buying behavior of organizations is generally considered to be different from that of individuals. *Rogers* explains in its DOI also the organizational innovativeness using three independent variables: 'individual (leader) characteristics', 'internal characteristics of organizational structure', and 'external characteristics of the organization' [41]. The Diffusion of Innovations theory therefore describes on a firm level the organization's innovation adoption behavior via management receptiveness towards innovation and change, descriptive characteristics of an organization and the receptiveness towards innovation of the firms environment. *Tornatzky and Fleischer*'s took up the ideas of the DOI in their TOE framework. They identify organizational characteristics and the environmental influences on the firm as variables influencing the adoption decision of firms. Additionally, the TOE assumes the three major factors being dependent on each other (cf. figure 2) [50]. A comparison of these two models on the firm level was published by *Oliveira and Martins*, including an overview over empirical validation of both [51].

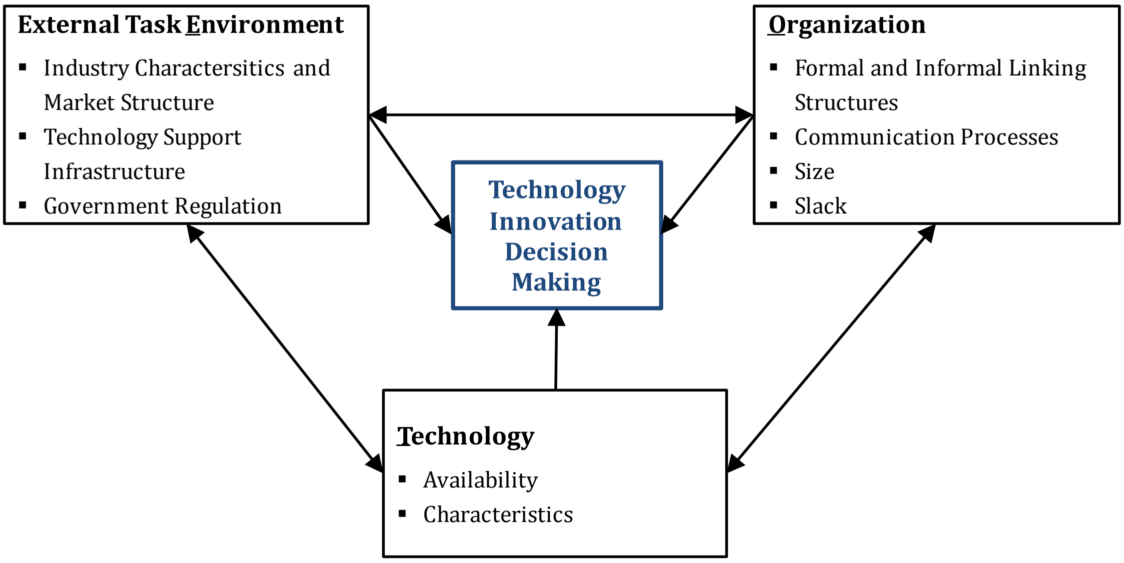

Figure - 2: TOE Framework based on [52]

Those broad theoretical implications are further classified by Frambach & Schillewaert who identified influencing factors on the acceptance of new ptechnologies by organizations: The adoption behavior is determined bythe 'perceived innovation characteristics', the 'adopter characteristics' and 'environmental influences'. As well, an organization's 'social network', the 'supplier marketing efforts' and also the 'environmental influences' affect the 'perceived innovation characteristics' of a firm [53].

The organizational adoption behavior for new products or technologies takes place in the setting of organizational buying processes. Thus, this specific process of acquiring new products and technology influences adoption behavior and the underlying criteria. An individual buying process is mostly described by more spontaneously and rather on point in time-oriented events, while firms buy more process-orientated. The process orientation of organizational buying brings with it several commonly agreed on characteristics that are both cause and effect of it. According to Webster & Wind four generic criteria to differentiate organizational from consumers' buying behavior can be identified: higher specifity of demand, higher number of persons involved, stronger tendency towards rationality and a longer purchase decision process [54].

Up to now, frameworks or models on organizational adoption behavior on automotive markets have not be tested empirically or validated. Nevertheless, the future market penetration of technologies reducing CO_2-emissions of HCV should be discussed in this specific B2B context.

3 Conceptual framework for HCV market forecasting

3.1 Identification of an appropriate modeling framework

Based on the findings demonstrated in section 2, it can be concluded, important drivers and barriers of technologies reducing CO_2 emissions in HCV are the technological characteristics itself, infrastructural constraints, policy instruments and the specific end-customer requirements. However, their general systemic interdependencies on the HCV market haven not yet been analyzed. DTSM have their strengths in providing simple adoption forecasts if there is no absence of solid quantitative data. ABM is advantageous in capturing the heterogeneity of a market, if the agents behavior and decision rules are empirically observed. SD is beneficial for understanding the basic and underlying market interdependencies and providing valuable qualitative insights in the absence of valid empirical data.It is hypothesized, the market penetration of new technologies differs between PC market and the HCV market. Further it is assumed the differences in adoption and buying behavior have a significant influence on this difference

As its one of the first studies for analyzing the diffusion of HCV technology, the overall understanding of principle market mechanism is the primary goal. This goal can be met in providing a comprehensive model incorporating the overall market dynamics. On this basis sensitive parameters/drivers of future market split can be outlined for guiding future work in this field of research. However, empirical data about the different stakeholder and their interdependencies is rare. As a conclusion, it is assumed System Dynamics fits best to the problem at hand. Therefore, a System Dynamics model is used for studying the principal characteristics of the future market penetration of technologies reducing CO_2 emissions in HCV at the exemplary use case of European long-haulage trucks.

This SD model is enriched by the DCM to describe the customers' decision process and rules. Additionally, the basics of innovation diffusion don't solely help to model the organizational adoption decision but also approximate the behavior of managers within the supplier and technology supporting infrastructure industry [36]. Finally the ABM is not explicitly used, however the principle concept of regarding multiple stakeholders as decision making agents supports a differentiated SD model implementation [30].

Sterman defined a widely used approach for developing such SD models, which guides further work: (1) identifying the questions to be addressed and determining the key variables, (2) formulating the dynamic hypothesis, (3) implementing a simulation model to test the dynamic hypothesis, (4) testing the model until it is comparable to reference modes and (5) designing and evaluating policies for improvement [55,56]. In this working paper, the process towards step 2 is presented and provides the basis for future research.

3.2 The European HCV market dynamics

Since this paper aims to propose a framework for the analysis of emerging technologies' market penetration on HCV market, the key variables are defined along the stakeholder involved and findings of organizational adoption of innovations. Studies on automotive market imply four general stakeholder: HCV industry, road freight forwarders, energy supply system, and policymakers. Those agents are complemented by the technologies itself, having changing characteristics caused by the HCV market dynamics. Figure 3 summarizes the organizational adoption framework for the HCV market.

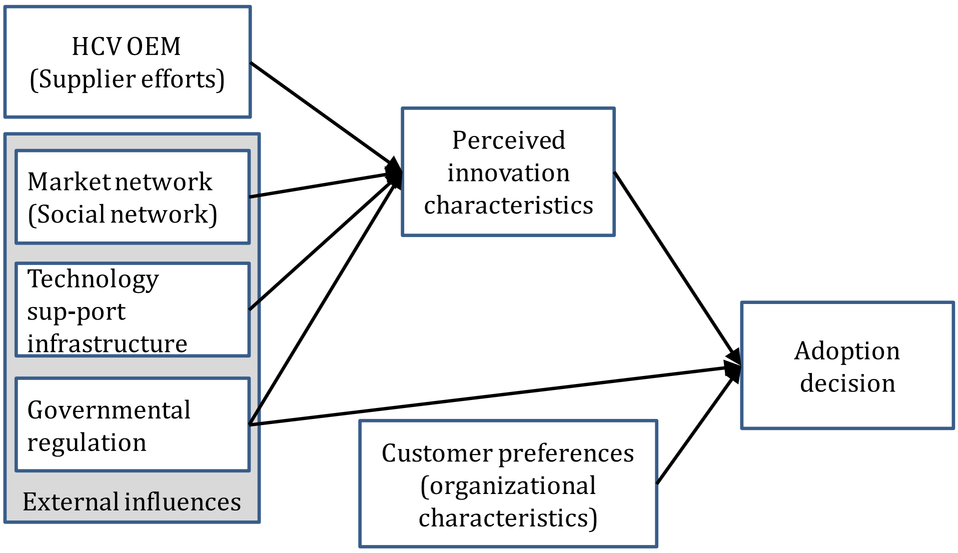

Figure - 3: Organizational adoption framework for the HCV market

To define model variables adequately, a cross-impact analysis of the stakeholder and technological options is conducted. Hereby, a set of influencing factors based on the stakeholder and market analysis is identified and ranked according to their active, passive and dynamic influence of all other factors. Thereby system variables (endogenous), external forces (exogenous) and minor relevant factors were identified [36,38,57–59] and assigned to the corresponding agents and subject of influence. Detailed overview and results of this cross-impact study are provided by Tables 1, 2 and Figure 5 in appendix. On this basis, the identified influencing factors are introduced from a stakeholder perspective framework.

Costumers are defined in this context as freight forwarders using HCV for long-haulage freight transportation. Although there is a huge variety of such companies – ranging from owner drivers to multinational companies – they are clustered in only two different customer groups: innovative and mainstream agents. Within these customer groups the agents are assumed having uniform as well as constant preferences and requirements. The investment decision upon new HCV, and thus a power train concept, is reached by an organizational process of a buying center according to the perceived technologies' characteristics, availability, and awareness.

HCV manufacturers (OEM) develop and offer commercial vehicles on the market. Due to simplicity the supplier industry is incorporated within this agent. No heterogeneous agents are assumed. The commercial vehicles can be purchased with the offered power train concepts available in different power classes. Based on the expected customer demands, governmental policies, and market trends, R&D expenditures are allocated for technology characteristics improvement and the expansion of power train concepts portfolio. The availability is defined as a decisive factor for the adoption decision. Therefore the concept of technology availability is introduced, which represents the variety of power classes of each model being configurable to the customer. Thus, a low availability reduces the probability of a power train concept to be chosen by a customer, due it is ineligible to its transport task.

Technology Support Infrastructure incorporates primarily the fuel stations and, in contrast to most PC market forecasting model, service points. Minimizing downtimes is playing an essential role for freight forwarders. Thus, service station density and vehicle availability are under the most important criteria for the buying decision [25]. For a big extend the technology service point development is driven by the OEMs, and only partly by independent agents or customer owned points. Thus, it is assumed, the service point built-up is linked to the HCV manufacturers' interest in power train concepts. In contrast, the fuel stations are influenced by independent operator agents and the customer itself. Moreover, many freight forwards are using their on-company site fuel station. In addition, freight forwarders are widely concluding contracts with a few of independent agents spread over their general cruising radius. In doing so, bulk consumer prices for fuel are achieved and costs so reduced. In summary considerably less fuel stations per sqkm are required compared to PC market. Hence the decision upon built-up or removal of fuel station is described by the type and volume of power train concepts sales in the market. A spatial disaggregation of technology support infrastructure, as shown in Struben (2006), is not used in the model. Instead a homogenous distribution is assumed [46].

Governmental Regulation is determined by an uniform agent, albeit there are varying national and European policies for the HCV market. The Government agent sets market regulations, fuel and vehicle standards, taxes, and incentives. Despite the fact governmental agent's 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 [45,60].

Perceived Technology Characteristics cannot be seen as an agent, since no decisions are made. However, the characteristics development doesn't underlie solely the agents' 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 [50], total cost of ownership, purchasing price sensitivity and basically on a intra-organizational perspective the perceived usefulness, perceived ease of use [53] and image to achieve social desirability [53,61,62].

External factors are outlined as exogenous effects out of the agents' behavior. In addition to the governmental regulation, primarily European energy prices and the economic growth 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).

Based on Struben, a dynamic hypothesis is an essential assumption for the SD model development and leds to the dynamic market framework. Previous studies on PC market forecasting have highlighted the chicken-egg problem in refueling infrastructure development for alternative fuel vehicles [35,36,46]. This accounts for the service station density for alternative fuel vehicles and other innovative technologies, too [25]. Additionally, the market network and social network are influencing the adoption decision. Those factors are primarily driven by the vehicle stock and thus the market shares. Moreover, policy makers' and OEM's actions are driven by the actual market development as well. Mau et al showed how customer preferences are changing with gaining market shares of innovative technologies [63]. Therefore, the adoption decision itself – resulting in higher sales of a new technology – has again an impact on the organizational adoption by influencing the social network, suppliers efforts, governmental regulation and the energy supply system. Therefore, a dynamic hypothesis of such market development is stated. The TOE-Framework for organizational adoption of innovations supports the dynamic hypothesis by defining the technological, environmental and organizational context being dependent on each other [50]. The dynamic hypothesis of the causal model is illustrated by incorporating findings of the HCV adoption framework with the cross impact analysis in Figure 4.

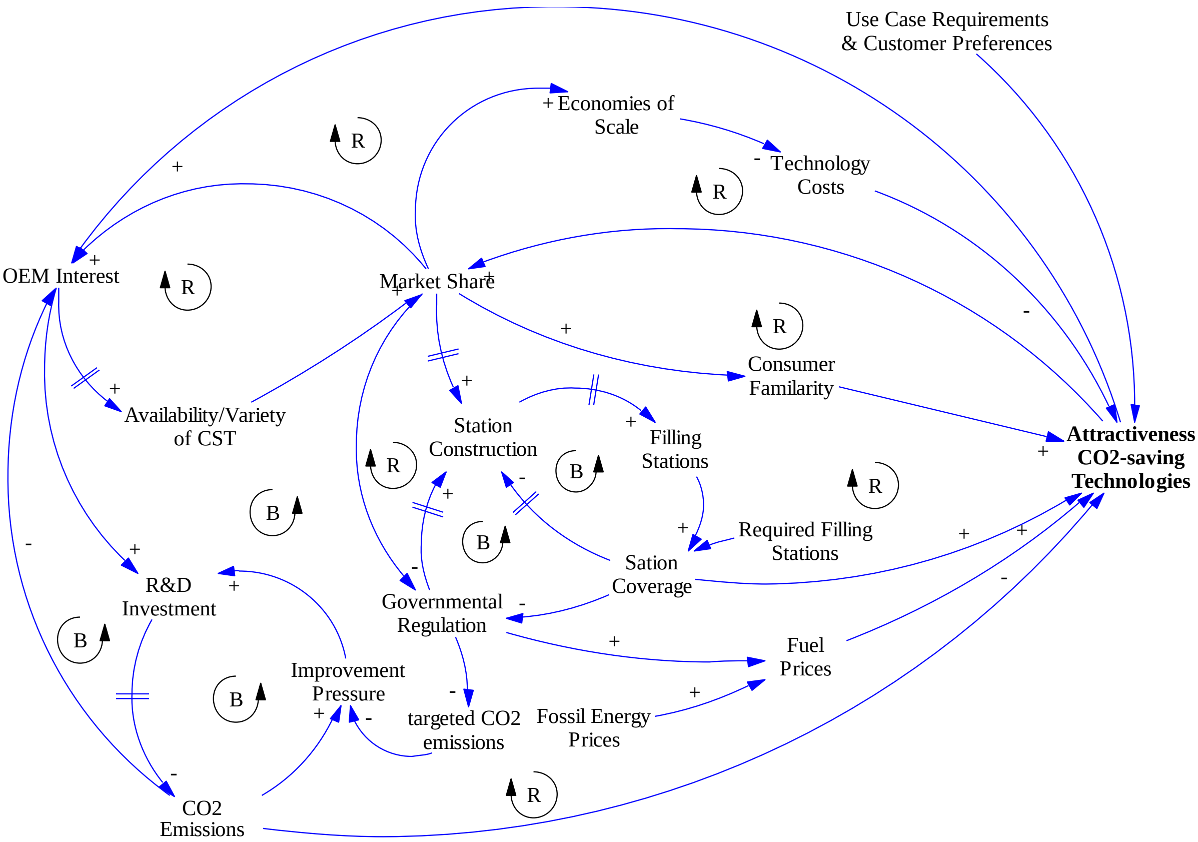

Figure - 4 Causal loop diagram of diffusion of CO_2-saving technologies on HCV market

4 Conclusion and Outlook

Summarizing, a causal conceptual framework for studying the technology diffusion on the HCV market using System Dynamics has been developed. Based on a meta-analysis of literature on market forecasting tools, HCV related market studies and organizational adoption of innovation a cross impact were conducted theoretically. The results revealed the most crucial factors for the successful diffusion of CO_2-saving technologies on the HCV market and were discussed on a stakeholder perspective. Furthermore, the underlying interdependencies of the stakeholder and influencing factors have been highlighted. The results are aligned with congruent phenomena of the chicken-egg problem in technology diffusion. The core interdependencies of different stakeholders are integrated into causal System Dynamics (SD) model and provide a basis for developing quantitative SD models for analyzing the future market penetration of CO_2-saving technologies on the HCV market to gain insights on GHG emissions reduction potential by alternative power trains in the European Transportation systems

For future research this framework should be quantified, applied and validated on the European market. Furthermore, we suggest deriving the influencing factors as well as the interdependencies on the market empirically. Additionally, a validation of the organizational adoption behavior for innovation on automotive B2B market could contribute significantly to the understanding of diffusion processes in this setting.

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Appendixes

Influencing Factors on Market Development of Technologies Reducing CO2 Emissions in Heavy and Medium Commercial Vehicles - A Technology View

Category	Nr.	Influencing factor	More detailed description
Powertrain concepts	1	*Fixed costs of PT concepts*	*Acquisition costs - incentives + interests PT concepts: Conventional Diesel, CNG, LNG, el. & hydr. Hybrid, WHR, BEV, FCV. Costs of whole PT concepts including engine (energy-conver-sion), energy storage, transmission, peripheral technologies*
	2	*Variable costs of PT concepts*	*Operating costs: Fuel, Maintenance, Taxes, ...*
	3	*CO2 Emissions of PT concepts*	*CO2 Emissions of PT concepts of total PT concept*
	4	*Exhaust Gas Management*	*Required exhaust gas management to meet regualtory standards*
	5	*Energy/Fuel storage*	*conventional fuel tank vs. Battery vs. CNG tank vs. LNG tank*
	6	*Economies of scale*	*Expected ratio of future cost degression*
	7	*Performance criteria*	*usability, durability, reliability, range, weight, volume, ~~TCO~~ [den Boer et al. 2013], ~~price,~~ power/torque, complexity*
Vehicle measures	8	Aerodynamic optimization of vehicle	*Costs & Benefits of measure, learning curve, durability, complexity, Competition vs. symbiosis of measures*
	9	Driver assistance systems	
	10	Lightweight	
	11	Reduction of rolling resistance	
OEM	12	Financial situation of OEMs	Financial capabilities to invest in R&D of new power train concepts and investments strategies
	13	Willingness to promote CO2 reducing technologies	Strategy of OEM to which degree CO2 saving technologies are developed beyond GHG emission legislation
	14	OEM technology preferences	(engine vs. peripheral vs. Vehicle measures: Which one to push/develop/focus on?
	15	Market introduction strategy	Market pull vs. Technology push vs. Regulatory forced
	16	Financial significance of technologies	Does a PT technology have a strong financial significance on an OEM?
	17	Availability of technologies	Availability of PT concepts in models and power segments
Energy	18	Crude Oil price	European Crude oil price
	19	Natural Gas price	European Natural Gas price
	20	Electricity price	National electricity price
Economical	21	Economic situation	Global, European and national CAGR of the economy
Societal	22	Connectivity	Trend of the internet of things and services
	23	Environmental awareness	Societal and political environmental awareness
	24	Pressure for CO2 - reduction	Degree of enforcement to reduce CO2 emission caused by global warming.
Political	25	Lobbying	Lobbying of Industry for their interests
	26	GHG emission legislation	GHG emission legislation on European (and national level) for fleets and/or single vehicles
	27	Pollutant emission legislation	NOX, CO, ...
	28	Truck dimension regulation	(length, weight, ...)
	29	Taxes and incentives	Fuel and vehicles taxation. Subsidies for vehicles or infrastructure measures
	30	Restricted emission zones	CO2 and pollutants
	31	Noise reduced zones	Noise reduced zones (Always/ day- or time-dependent) in cities
Automobile industry	32	Natural Gas storage technologies	Development of CNG and LNG tanks
	33	CV After Sales Business	LPG retrofitting, etc.
	34	Battery energy/power density	Technological development of Lithium Ion / Air batteries
	35	Battery costs	Cost of Lithium Ion / Air batteries
	36	R&D power train focus	Industry focus of power train R&D
	37	Competencies Tier 1 & Tier 2 supplier	Development of tier1 and tier2 suppliers competencies regarding performance quality costs or innovation
	38	Life span of commercial vehicles	
Non CO2-reduction-related	39	Connected vehicle	Degree of connectivity of components and vehicles to the internet
	40	Telematics	Telematic functions of CV
	41	Comfort	Comfort issues of CV
CV market supporting industry	42	Service infrastructure (local, national, European)	Development of local, national and European service infrastructure for new technologies
	43	filling/loading infrastructure	Development of local, national and European density of CNG/LNG fuelling stations and (fast) battery charging points
	44	New technologies specialized CV dealer and workshops	Density of dealers and workshop licensed for new technologies

Automotive markets	45	CV Dealer's attitude towards new tech.	CV Dealer's attitude towards new technologies, intensity of training on new technologies
	46	Knowledge transfer PC --> CV	Technical and system know-how transfer from PC to CV
	47	Market share of alt. PT Technologies PC	Market share of alt. PT technologies on PC markets
	48	Bio fuels	
	49	2nd life CV market	Needs and regional distribution of 2nd life market customers
	50	Structure of the CV market	Development of different Use Cases and totally new segments
Mobility, traffic & transport	51	Transportation modes	Split of transport modes (Air, water, rail, road), transport providers.
	52	Traffic systems	Structure and development of goods and passenger traffic, traffic control system
	53	Driver's attitude towards new technologies	Driver's attitude towards new technologies, their acceptance and training on new technologies
	54	Market volatility	Market volatility of road transport market in tkm/a
Customer	55	Customer preferences	Development of customer needs. Importance of price, tco, performance etc. Criteria for buying decisions
	56	Use Case requirements	Segmentation of Use Cases. Requirements on CVs by driving patterns, transport goods, yearly mileage, ...
	57	Required period of amortization	Required period of amortization of additional measures taken at CVs
	58	Period of usage	Average period of usage per Use Case of CV
	59	Awareness of technologies	Awareness/popularity of new technologies among CV customers
	60	Driving cycles	Driving patterns (Share Urban, Extra Urban and Long Distance) of CV customer
	61	Diesel image	Image of conventional Diesel power train
	62	Mode of investment	Share of investments in CV of Cash/Leasing/Financing/Rental

Table - 1: influencing factors on the market development of CO_2-saving technologies in HCV

Einflußmatrix

Wie stark beeinflußt Einflußfaktor A (Zeile) Einflußfaktor B (Spalte)?

Bewertungsmaßstab:
0 = kein Einfluß
1 = schwacher, verzögerter Einfluss
2 = mittelstarker Einflusss
3 = starker, unmittelbarer Einfluss

#	Factor	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62		
1	Fixed costs of PT concepts		1	2	3	2	3	2	1	1	2	1	1	1	3		2	3											2						1	2		3	1				1	2	1	3				2	1		1		3		3	2	3		2	3	64	0,74
2	Variable costs of PT concepts	1		3	1	3	1	3	2	2	2	2		1	2			3								2	1		1			2	1		1	1		1	1				1		1	3			3	2	1		2		3		3	2	3	1	2	3	67	0,79
3	CO2 Emissions of PT concepts	1	3		1	2	2	2	2	2	2	2		2	3			3	1	1					2	3	1		3	3	2	1		2	1	2		1	1						3			3	1	1	1	1	1	3		3	3	3	1	2	1	78	0,80
4	Exhaust Gas Management	3	2	3		1	1	1			1			2			2								1	2		3	2			1						1							1			2	2					2		2		1		3		39	0,74
5	Energy/Fuel storage	3	2	3	1		2	1			1				2			2								1		1	3			3	1	3	3										3		3			1	2	1	2	2		2		2	1	3	1		2	57	0,67
6	Economies of scale	3	1	1	1	2			2	2	2	2	1	1	1		1	2									1								1	2	3	1		3					2	2	1	1				1			1		2		3	2	2			2	52	0,61
7	Performance criteria	2	2	3	1	1			1	1	1	1			2			3									1					1	1	1		3	2			3			1	3		1	3			2	2	1	2	3		3		1	3	3		3	2	63	1,34
8	Aerodynamic optimization of vehicle		3	3	1		1	1		1	1	1		1	2			1									1		3	1																		1				1			1		1		1		1			1	28	0,62
9	Driver assistance systems		3	3	1	1		1	1		2	2		1	2			1									1			1												2	2						1				1			2		1		1		1			1	32	0,62
10	Leightweight	1	3	3	1	1	1	1	1	1		1		1	2			1									1			1					1															1									1		1		1			1	26	0,57
11	Reduction of rolling resistance		3	3	1		1		2	1	1			1	2			1									1			1	1	1		1										1				1				1					1		1		1			1	28	0,67
12	Financial situation of OEMs	1		1		1	2	1						2	2		2	3									2										1	1	1	1		3		1	1	1	1		2		1			1				1								3	36	3,27
13	Willingness to promote CO2 reducing technologies	2	2	3	1	1	1	1	3	3	3	3			2			3									3	1	1		1				2		3	2	2	1							2		3	2	2		2	1			2		2		1		2		2	2	67	1,26
14	OEM technology preferences	3	1	1	1	2	1		2	2	2	2		2				3									3		1		1				3		3	3	3	2	1		1	1	1	1		2	2	1		2	2			1		2		1	1	2		2	3	67	0,81
15	Market introduction strategy	1																																				1							2		3	2						1			2		1	1	2			3	19	####
16	Financial significance of technologies	2		1		1	1	1	1	1	1	1	1	2	3			2									3											3	2	2		1					1		2	1	1								2		1				3	40	3,08
17	Availability of technologies	2				1	3		1	1	1	1		3	3		1									2	2	2		2			2		2	2	3	2							3	3	3	2			2	3		1	3		2			2	3			1	64	0,74
18	Crude Oil price	1	3	2		2	2	1	3	3	3	3	1	3	3		1	3		2	3	2			2	2	2	1		2	1		2	1	1	2	3									2	1	1		1	3	1	3	1	2	2	2	1	2		3		3		88	5,87
19	Natural Gas price	1	3	1		2	1		1	1	1	1		2	2		1	2	1		3	1				1	2	1		1		1	2	1		1	2									2	1			1	3	1	3	1	1		1		2		3		1		56	2,95
20	Electricity price	1	2				1								1	1			1	1	2								2		1		1				2	2										2				1	2		3	1			1		2		1				31	3,10
21	Economic situation		1	2		1	1		1	1	1	1	3	3	1		2	2	3	2						3	1	1		3						1	1	1		2	2				1	2		1		1	1	3	1	1	2	3	2	2	3	2				3	68	22,67
22	Connectivity		1	1						3					1			1																								3	2																2	1			1			1	17	8,50
23	Environmental awareness	2	1	3	3		2	1	2	2	2	2		2	1			2		1						2	3	3	1	3	3	3			2	2	1		1						1	1	2	2	1	3	2	1	3	2	2	1	3		2		3		2		81	27,00
24	Pressure for CO2 - reduction	2	2	3		1	2	1	3	2	2	2		3	1			2	1	1								3		3	3	3	3			2	2	1		1						1	1	2	2	2	3	2	1	3	2	2		3	1	2		3		2		81	16,20
25	Lobbying	1		1	2	2			1	1	1	1							2	1								3	2	3	2	2	2						1											2			2		1	1	1		2									37	0,86
26	GHG emission legislation	3	2	3		2	2		3	2	2	2		3	2			3									2		2		3	1	1			1	1	3		1	1				1	1	1	2	1	3	2	1		3	1		1	3	1	1	2		1		70	2,19
27	Pollutant emission legislation	3	2	2	3	1	1			1				1	1			1									2				3	1	1			1	1	3		1	1				1	1	1	2	1	3	1	2	1	3	1		1	3	1	1	2		2		57	1,97
28	Truck dimension regulation	1	1	3		3			3		2	2		1	3			2									2				3						2	1	1		1	1								2	1			1		2	2		1	3	1	1	1				47	1,96
29	Taxes and incentives	3	3	3	2	1	2	1	1	1	1	1		2	3		1	3	3	3	2					2		1			1	1			2	3	1		1	1				1	3	1	3	1	3	3	2	2	2	1		3								3	77	1,24
30	Restricted emission zones	2	1	2	3	2	3	1		1	1			2	1			2									2		2		1		2			1	1	1												2	1	3	1	3	3	2	2			3	1	1	2	1	2		58	1,87
31	Noise reduced zones	2	1	1		2						1		1	1			1		1						2		2		1	2				1	1	1													2	1	3	1	2	3	2	2			3	1	1	2	1	1		46	1,44
32	Natural Gas storage technologies	3	2	2		3	2	2								2			2													2	2		2		1	1	1												3		1	2	2	1		1				1		2	1	2			1	44	0,80
33	CV After Sales Business	2	1		2		1		1					1	1			1																			2		1	2									1		2	1				2					1			1						23	1,00
34	Battery energy/power density	1	3	2		3		3							1	3			3		1	1					2		1	2	2	1	2	1	2		3														2	2		2	1	1	1		2		1	1		1		2	53	0,82
35	Battery costs	3	2	2		2	3	1					1	2	3		1	3								2		1	1	2	1	2	1	2	3		1												1	1	3	1	2		1			3		3		2			2	58	0,73
36	R&D powertrain focus	2	2	2	2	2	2	1	1	1	1	1						3														1	1	3		3	3		1	2						2		2		3	1	1						1									44	0,79
37	Competencies Tier 1 & Tier 2 supplier	1	1	2	2	2	2	1		2	1	1		1	3			2								1							3		3	3	3		3		1	1	1	1				3	2																46	3,83
38	Supplier competition	2	1	1		1	2						1				1																2	1	2	2		2												1	1							1	1				1		1		24	0,92
39	Life span of commercial vehicles	2		2	2		1		1				1																				3	1	1	1							2				1			3		1	1		1			3					2	29	1,53
40	Connected vehicle		1	1						3						1			1					1														1							3																	1		1	1	1	1				1	18	0,75
41	Telematics		1	1						3						1								1							1	1	1										2																	1		1	1	1						1	17	0,74
42	Comfort																																																						1		1								2	0,13
43	Service infrastructure (local, national, European)		2	1		3	1	2		1				1	2			2															1		1		2	1											2	3		1	1	1	3	1	3			2	1	1		3				3	45	0,75
44	filling/loading infrastructure		2	1		3	1	2						1	3			3	1	2	1					1		1	1			2	3		1	1	1									3		1	2		3	2	2	1	3	3		3	1	1		3		1		60	1,22
45	New technologies specialized CV dealer and workshops		1	1		3	1			1						1			1														1		2		1	1											3	2		3				1	1	2	2		3				2			2	35	0,69
46	CV Dealer's attitude towards new technologies			1	1	2	3	1	3	3	3	3			1			1																1	1		1					1	1	1	2		3				1	1			2		3				2		1	1	44	0,58
47	Knowledge transfer PC --> CV	2	2	2	2	2	3	1	1	1	2	1		1	3			1																	2		3	2	1				2		2	2	1					1											1					41	1,24
48	Market share of alt. PT Technologies PC	2	2	2	1	2	3							1	2			2							1	1					1			3		2	3	1							1	3	1	2	2		2	1		3	2		2				3			1	52	1,11
49	Biofuels		1	3	3										1			1	2	1										1				1	1												2				2		1														20	0,33
50	2nd life CV market	2				2	1		1	1	1	1	1	2	2			2																	2	2	1	2				2	1	1	1	3	1		2						1	1	1	2		3	3	1			2	48	0,60
51	Transportation modes																													1	1	2	2	2					1							2										3		2	1	2				1		2	22	0,48
52	Traffic systems																			1				1	1			1	2	1	2	2	1		1	1	1							3	1				2			3		1		1	2				1		2	31	0,57
53	Driver's attitude towards new technologies	2	3	3	2	2	2	3																									1		1	1	1				2	2		2	2	2	2			2	1		1			3				3		3	1	47	0,70
54	Market volatility	1																																										1	1	1	1		2		3	3	3	1		3	3	2	3		1		3	32	2,46
55	Customer preferences	3	1	1	1	3	3	3																	1	1	1		1	2				2		1	2	2	1			3	3	3	2	2	3	3	2		3	2	2	1	3				3	3	3		3	3	76	0,71
56	Use Case requirements	2	3	1	1	2	2	3																			1			1	3			2				2	2		2	2	2	2	2	1	1	2	1			3	2	1	2		3		1	3		2	1	3	61	1,79
57	Required period of amortization	2		2	2	2	2	1																												3	1												1			1	2						3			1			1	3	27	0,38
58	Period of usage	1		1	1	1	1																											1		2																1	3			2		3		3						3	23	0,46
59	Awareness of technologies	1		1	1	2	2																							2			2		1	1	1	1			2	2	2	2	2	3	2		1	2	3			2		3						1		42	0,51
60	Driving cycles	2	3	2	2	2	2	3																								1																		1			1		3	3	3	3				1	32	2,91
61	Diesel image	1				1	1																																												1			2	1			1		1				1				10	0,24
62	Mode of investment	3	2	1	1	2	2																									1			3				2	1	2		3	1	1	1				3			1	1	1		3	3	1				39	0,50
		87	85	98	53	85	80	47	45	52	46	42	11	53	83		13	86	15	19	10	3	2	3	5	43	32	29	24	62	31	32	55	23	65	79	56	12	26	19	24	23	16	60	49	51	76	33	47	61	80	46	54	67	13	107	34	71	50	82	11	42	78	2786	

Table - 2 Array of influencing factors on diffusion

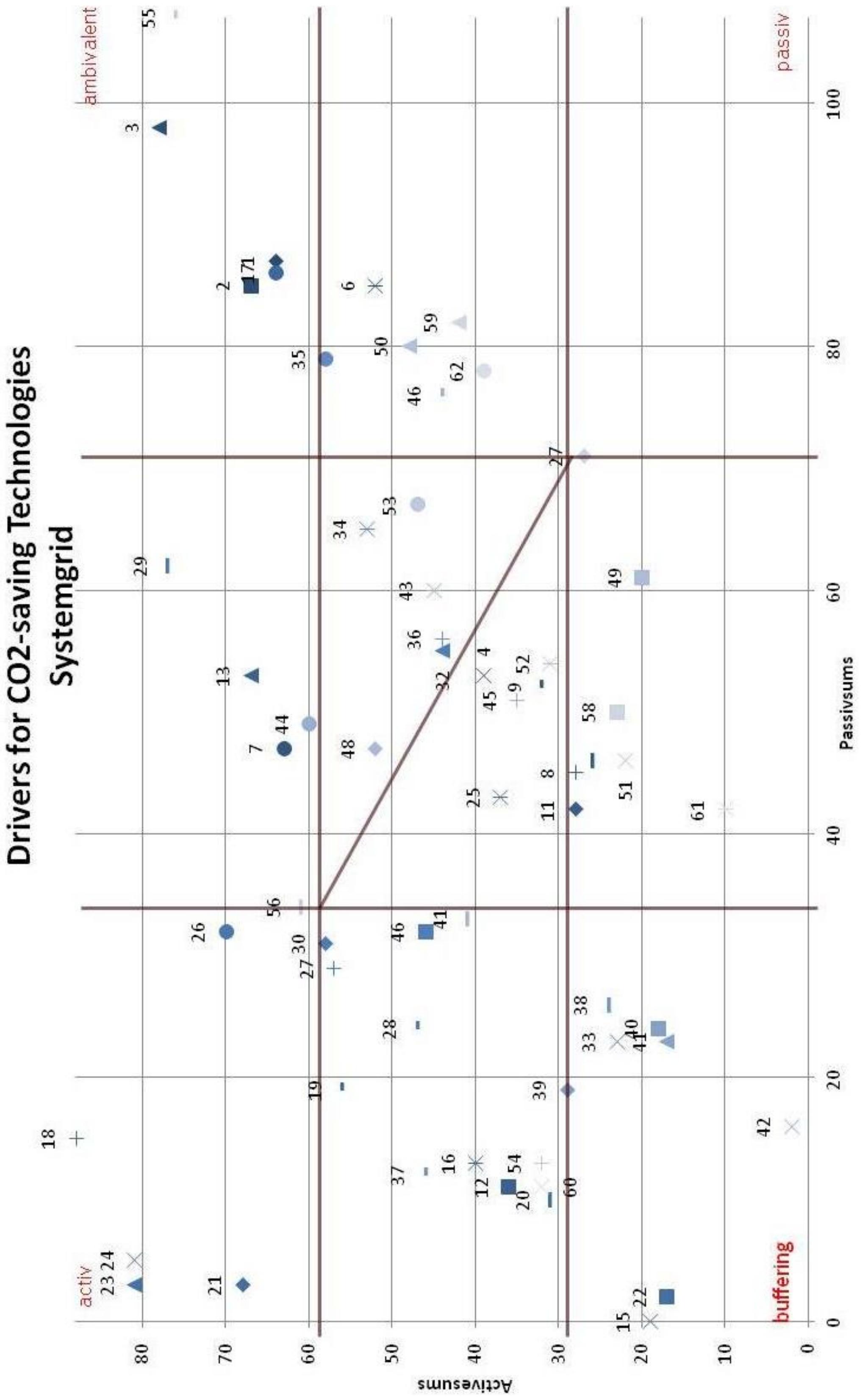

Figure - 5 Systemgrid of influencing factors

KIT Scientific Working Papers
ISSN 2194-1629
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