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THE TRANSITION OF ROAD TRANSPORT TOWARD AUTONOMOUS AND ALTERNATIVE FUEL-POWERED HEAVY-DUTY TRUCKS IN GERMANY

Dissertation
for obtaining the degree of Doctor of Business and Economics
(Doctor rerum politicarum - Dr. rer. pol.)

at WHU – Otto Beisheim School of Management

March 2020

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Acknowledgments

First and foremost, I would like to express my sincere gratitude to Prof. Dr. Stefan Spinler and Prof. Dr. Carl Marcus Wallenburg for their continuous support and guidance in my research. I would like to thank Prof. Dr. Stefan Spinler, my main advisor, for granting me the academic freedom to explore research areas that I am particularly passionate and interested about. His insightful supervision, trust, and methodological advice throughout all research projects are very much appreciated.

A special thank you goes to Marco Prueglmeier, Dr. Thomas Irrenhauser, and all other colleagues who have supported me with their industry expertise and invaluable encouragement throughout my research.

Last but not least, this dissertation would not have been possible without the support and understanding of my family and friends, especially my parents Elisabeth and Ralph Anderhofstadt, and my grandparents Ilse and Dr. Dr. Alfons Anderhofstadt as well as Betty and Simpert Hafenmeier.

Abstract

The trucking industry is at the beginning of a radical change due to several megatrends which will reshape the industry significantly. Based on the targets of the Paris Climate Agreement, the German government adopted its own Climate Action Plan 2050 which includes sector-specific reduction targets to reach a greenhouse gas neutral society by the middle of the 21st century. By 2030, the German Climate Action Plan specifies a reduction target of 40% from transportation compared to the reference year 1990. While emissions from other sectors such as energy or industry have decreased significantly since then, emissions from transportation remained stable. Among the various modes of transportation, passenger cars and commercial vehicles are by far the largest emitters of greenhouse gas emissions. As of January 2019, 99.7% of heavy-duty trucks registered in Germany run on diesel while the number of alternative fuel-powered passenger cars increases steadily. Apart from rising emissions, the industry faces a severe shortage of qualified truck drivers. According to the German Association of Freight Forwarders and Logistics Companies, the industry was facing a shortage of 45,000 drivers in Germany in 2017 with increasing tendency due to higher trade volumes and e-commerce.

This dissertation aims to discuss the transition of road transport in Germany toward innovative heavy-duty trucks. The main body of this dissertation consists of three research papers each of them focusing on autonomous and/or alternative fuel-powered heavy-duty trucks. The first research paper presents the results of a Delphi study with experts from industry and academia on factors affecting the purchasing decision and operation of alternative fuel-powered heavy-duty trucks in Germany. In the second study, a choice-based conjoint experiment with employees from freight companies was conducted to test how customers value the main attributes of innovative heavy-duty trucks. The Generalized Bass diffusion model was applied in the third study to investigate the future diffusion of battery electric heavy-duty trucks considering total-cost-of-ownership reduction effects.

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List of Abbreviations

ACEA	European Automobile Manufacturers Association
AFP	Alternative fuels and powertrains
BE	Battery electric
β_1	Effectiveness of external variable
BEV	Battery electric passenger car
BM	Bass diffusion model
BMU	German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
BMVI	German Federal Ministry of Transport and Digital Infrastructure
CBC	Choice-based conjoint
CNG	Compressed natural gas
CO	Cost of operation
CO_2	Carbon dioxide
CV	Coefficient of variation
Destatis	German Federal Statistical Office
DSLV	German Association of Freight Forwarders and Logistics Companies
EC	European Commission
EEA	European Environment Agency
EIO	Eco-Innovation Observatory
EPA	Environmental Protection Agency
EU	European Union
F(T)	Previous adopters and sales
f(t)	Sales forecast
FC	Fuel cell
FCE	Fuel cell electric
GBM	Generalized Bass diffusion model
GHG	Greenhouse gas
HB	Hierarchical Bayes
HDT	Heavy-duty truck

HDV	Heavy-duty vehicle
HVO	Hydrotreated vegetable oil
i	Interest rate
IQR	Interquartile range
KBA	German Federal Transport Authority
kW	Kilowatt
kWh	Kilowatt hour
LNG	Liquefied natural gas
LSP	Logistics service provider
m	Market potential
MHDT	Medium- and heavy-duty truck
NGVA	European Natural & Bio Gas Vehicle Association
OECD	Organisation for Economic Co-operation and Development
p	Coefficient of innovation
PP	Purchase price
q	Coefficient of imitation
RLH	Root likelihood value
RV	Resale value
SAE	Society of Automotive Engineers
TAM	Technology Acceptance Model
TCO	Total-cost-of-ownership
TPB	Theory of Planned Behavior
TRL	Technology Readiness Level
TtW	Tank-to-Wheel
UBA	German Environmental Agency
UTAUT	Unified Theory of Acceptance and Use of Technology
VAT	Value-added tax
WHO	World Health Organization
WtT	Well-to-Tank
WtW	Well-to-Wheel
x(t)	Mapping function

1. Introduction

"The automotive industry is in the midst of a fundamental change" declared Harald Krüger, former CEO of BMW, at the International Motor Show in 2017 and refers to several disruptive megatrends which hit the industry at the same time (BMW, 2017b). For instance, the first mandatory European carbon dioxide (CO_2) standards for new passenger cars were introduced in 2009 which set a fleet-wide average emission target of 130 grams of CO_2 per kilometer from 2015 onwards. By 2021, carmakers need to reach a stricter target of 95 grams of CO_2 per kilometer in order to avoid penalty payments (EC, 2020a). Moreover, new competitors such as Tesla entered the market which need to be taken seriously, especially by German premium companies. However, the American producer of electric vehicles surpassed most of the established car manufacturers in terms of market capitalization and increased the number of new registrations in Germany by 462% from 2018 to 2019 (KBA, 2020b). Apart from strict environmental regulations which force car manufacturers to shift their production towards electrification, the industry is undergoing a radical change due to other megatrends such as connected vehicles and self-driving technology. As cars are becoming more complex and intelligent, financially strong tech giants decided to invest in the future of mobility. For instance, Google started its own self-driving car project in 2009 which was renamed Waymo and is now a wholly owned subsidiary of Alphabet, Google's mother company (Waymo, 2020a). Hence, traditional car manufacturers need to invest huge amounts in low-emission vehicles, shared mobility and autonomous driving in order to reach defined emission targets, keep technological pace with strong competitors and to deal with raising awareness concerning environmental protection in today's society.

This fundamental change does no longer affect carmakers only but now applies also to manufacturers of heavy-duty vehicles (HDVs). Compared to passenger cars, the trucking industry is not in the midst of a radical change but at the very beginning. Accordingly, there exist several parallels between the car industry in the 2010s and the current situation of truck manufacturers. For instance, ten years after the first European CO_2 standards for passenger cars were defined, CO_2 reduction targets for HDVs were specified for the first time in 2019. From 2025 onwards, manufacturers of HDVs must achieve a reduction of 15% of fleet-wide average CO_2 emissions compared to the reference period from July 2019 to June 2020 (EC, 2019b). Similar to automakers, new competitors such as Nikola Motor enter the European

truck market with intelligent and fully electric vehicles. In February 2020, CNH Industrial, the mother company of the Italian truck manufacturer IVECO, announced that they have invested 250 million US-dollars in the American truck startup. The first version of the Nikola TRE, a modified version of the conventional IVECO S-Way, will be a battery electric (BE) truck and complies with all European requirements. The second version of the Nikola TRE will be a hydrogen-powered fuel cell electric (FCE) truck which will be introduced to the market in 2023. Both versions of the Nikola TRE will be built at the IVECO plant in Ulm, Germany (IVECO, 2020). In addition, the self-driving specialist Waymo, but also other firms, started to test autonomous trucks by adapting the existing car technology to heavy-duty trucks (HDTs) (Waymo, 2020b).

Climate change is commonly seen as one of the biggest challenges of the 21st century, hence, certain megatrends such as electric mobility are also driven by environmental concerns. The World Health Organization (WHO) argues that "the transport sector is the fastest growing contributor to climate emissions" (WHO, 2020) and the European Commission (EC) states on its website that "transport represents almost a quarter of Europe's greenhouse gas emissions and is the main cause of air pollution in cities" (EC, 2020c). In 2016, road transport accounted for 21% of total CO_2 emissions in the European Union (EU) and according to the EC, 6% of the overall EU CO_2 emissions are produced by HDVs (EC, 2019b, 2020b). In order to fight climate change and to realize a carbon neutral society, 189 of 197 countries including Germany have already ratified the Paris Climate Agreement which aims to keep global temperature increase well below two degrees above pre-industrial levels (UNFCC, 2020). Germany is by far the largest emitter of greenhouse gas (GHG) emissions in the EU but is committed to the Paris Climate agreement and plans to drastically reduce emissions across all sectors. As a requirement of the agreement, the country adopted the German Climate Action Plan 2050 which specifies emission reduction targets for each sector (BMU, 2020). By 2030, the German government aims to reduce GHG emissions from transportation by at least 40% compared to the reference year 1990 but emissions decreased by 1% only from 1990 to 2018 (BMU, 2019a). Based on statistics from the German Federal Motor Transport Authority (KBA), registration numbers of alternative fuel-powered passenger cars are clearly increasing whereas low-emission HDTs remain a rare species on German roads (KBA, 2019).

Another megatrend which will drastically reshape the car and trucking industry is self-driving technology. While autonomous cars have the advantage of a more pleasurable experience for their passengers, the technology offers several business-related benefits for freight companies. Fritschy and Spinler (2019) describe, among others, reduced costs for drivers, enhanced safety or optimized fuel efficiency as important advantages of autonomous trucks. However, one of the biggest challenges in the logistics and transportation sector is the shortage of truck drivers. Mittal *et al.* (2018) refer to the increase of e-commerce and higher trade volumes what leads in turn to a higher demand for drivers. The authors argue that this is a global problem, but some countries particularly suffer from a severe shortage of qualified drivers such as Japan, the United States or Germany. Hence, truck manufacturers started to invest heavily in the series development of highly automated trucks. For instance, Daimler Trucks announced at the 2019 Consumer Electronics Show in Las Vegas that they are spending half a billion Euros in self-driving technology for trucks (Daimler, 2019a).

Previous research with respect to alternative fuels and autonomous driving mainly focuses on passenger cars. Even though the trucking industry now faces similar challenges as the car industry some years ago, the results are often not applicable to HDTs due to the differences in vehicle weight, engine power or annual mileage driven. This dissertation focuses on the future of innovative HDTs in Germany as important boundary conditions vary among countries with respect to relevant cost parameters, financial or non-financial subsidies, regulatory requirements or the number of available fueling/charging stations for alternative fuel-powered trucks. Moreover, Germany is by far the largest emitter of emissions in the EU and aims for a carbon-neutral society by 2050 but while emissions from other sectors decreased significantly since 1990, emissions from transportation remained almost at the same level. In addition, the country is not only an important manufacturer of cars but also a dominant global player in the commercial vehicles sector. For instance, the German manufacturer Daimler Trucks is the leading truck company worldwide and sold more than 488,000 vehicles in 2019 based on the latest annual report (Daimler, 2020b). Nonetheless, to cope with the described challenges, a close collaboration from several stakeholders will be inevitable to realize a successful transition toward a new era of innovative HDTs in Germany.

The main body of the dissertation consists of three research papers each of them analyzing autonomous and/or alternative fuel-powered HDTs in Germany. The following chapter

presents the results of a Delphi study on factors affecting the purchasing decision and operation of alternative fuel-powered HDTs. The Delphi method is an anonymous, multi-stage survey technique which relies on the experience, industry perception and knowledge of an expert group, the Delphi panel. The third chapter includes the results of a choice-based conjoint analysis with employees from freight companies in Germany. Conjoint analysis is a well-established multivariate statistical research method which was utilized to analyze the importances and part-worth utilities of the main attributes and levels of autonomous and alternative fuel-powered HDTs. In addition, future scenarios were designed in cooperation with an expert group to simulate future customers' preference shares for innovative trucks. The fourth chapter analyzes the future diffusion of BE HDTs in Germany as it is currently the only viable technology for locally emission-free road freight transportation. The Generalized Bass diffusion model, a modified version of the traditional Bass model, was applied to forecast the market penetration in Germany considering total-cost-of-ownership reduction effects as an external variable. Despite the practical relevance of the three chapters, guiding theories were incorporated and helped to orchestrate the execution of this research.

2. Factors affecting the purchasing decision and operation of alternative fuel-powered heavy-duty trucks in Germany

The following chapter is based on Anderhofstadt and Spinler (2019) 'Factors affecting the purchasing decision and operation of alternative fuel-powered heavy-duty trucks in Germany – A Delphi study' [1]

2.1. Introduction

The Kyoto Protocol is considered a milestone in international climate change as it was the first agreement that includes binding targets to reduce greenhouse gas (GHG) emissions. The protocol was adopted in December 1997, entered into force in 2005 and has been ratified by 191 countries including Germany (BMU, 2019b). The targets of the agreement cover the six main GHGs: carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride (UNFCC, 2019a). CO_2 is the primary GHG emitted through human activities as stated by the United States Environmental Protection Agency (EPA). CO_2 is naturally present in the atmosphere as part of the Earth's carbon cycle, but human-related actions such as fuel combustion for transportation are altering this cycle. By emitting CO_2 to the atmosphere, human activities have substantially contributed to climate change since the Industrial Revolution in the 18th century (EPA, 2019).

In 2017, global CO_2 emissions hit a new record high with a total of 36,153 million tons and have increased by 63% since 1990. The United States and China are the top CO_2 emitters worldwide. Since 1990, CO_2 emissions in the United States have increased by 2.9% from 5,121 million tons to 5,270 million tons in 2017. Meanwhile, CO_2 emissions in China rose by 306.6% from 2,420 million tons to 9,839 million tons. However, when comparing CO_2 emissions per capita in 2017, the United States was ranked 11th with 16.0 tons and China 52nd with 7.0 tons. Most CO_2 emissions per capita were emitted by Qatar with 49.0 tons which was ten times higher than the global average of 4.8 tons in 2017 (Global Carbon Atlas, 2017; BMU, 2018).

[1] Anderhofstadt, B. and Spinler, S. (2019) 'Factors affecting the purchasing decision and operation of alternative fuel-powered heavy-duty trucks in Germany – A Delphi study', Transportation Research Part D: Transport and Environment, 73, pp. 87–107.

With a total of 799 million tons of CO_2 emissions in 2017, Germany was the largest emitter in the European Union (EU), the 6th largest worldwide and contributed approximately 2.2% to global CO_2 emissions. However, CO_2 emissions in Germany fell by 24% from 1,053 million tons in 1990 to 799 million tons in 2017. Likewise, CO_2 per capita decreased from 13.0 tons in 1990 to 9.7 tons in 2017 ranked 33rd worldwide (Global Carbon Atlas, 2020).

To achieve GHG neutrality by the middle of the century, the German government decided on a strict pathway for emissions reduction and adopted the "German Climate Action Plan 2050" in 2016. It specifies emission reduction targets for different sectors for the first time and provides guidance for a successful transition to a GHG neutral society (BMU, 2018). According to the German Environmental Agency (UBA), CO_2 accounted for 88% of total GHG emissions (909 million tons) in Germany in 2016 (UBA, 2018). Most GHG was emitted by the energy sector (343 million tons), the industry sector (188 million tons) and the transport sector (166 million tons) (BMU, 2017b). The first milestone of the climate action plan is to reduce emissions by 2030 relative to 1990 levels from the energy sector by 61%, from the industry sector by 49% and from the transport sector by at least 40%. While GHG emissions from energy could be reduced from 1990 to 2016 by 26% and emissions from industry by 34%, GHG emissions from transport even increased by almost 2% (UBA, 2015).

In 2016, GHG emissions from transport exceeded the level from 1990 for the first time since 2004 (see Fig. 25 in the appendix). National aviation was responsible for 1.4%, shipping for 1.2% and rail transport for 0.6%. Thus, passenger cars and commercial vehicles accounted for almost 96% of total emissions from transport in Germany while the latter contributed 35.3% and the former 60.6% (BMU, 2018). For instance, total freight transportation in Germany rose from 400 billion ton-kilometers in 1991 to 655 billion ton-kilometers in 2016. Meanwhile, the share of road freight transportation related to the total freight volume increased from 61.4% in 1991 to 70.4% in 2016 (UBA, 2018). Although specific energy consumption per ton-kilometer has fallen due to the improvement of engine efficiency, emissions from commercial vehicles have increased by roughly 50% since 1990 as increasing road freight transportation led also to an increasing number of commercial vehicles (BMU, 2018).

There exist five truck classifications based upon payload capacity, according to the German Federal Motor Transport Authority (KBA). We focus on the heaviest categories, heavy-duty

rigid trucks with a minimum payload capacity of 12 tons, as well as on heavy-duty tractor units. Fig. 26 in the appendix illustrates the difference between rigid trucks and tractor units. Both types will be summarized as heavy-duty trucks (HDTs) in the remainder of this study.

Latest registration numbers for passenger cars and HDTs in Germany are summarized in Table 1. Although passenger cars are dominated by petrol and diesel, 787,293 (1.7%) of registered vehicles are already powered by alternative drives. On the other hand, almost 100% of registered HDTs run on diesel and only 159 (0.05%) on alternative drive technologies (KBA, 2018a).

Table 1: Registered passenger cars and heavy-duty trucks in Germany as of January 2018 (based on KBA, 2018a)

	Passenger cars		**Heavy-duty trucks**	
Drivetrain	**Units**	**Percentage**	**Units**	**Percentage**
Petrol	30,451,268	65.52 %	145	0.044 %
Diesel	15,225,296	32.76 %	328,661	99.728 %
Natural Gas	496,742	1.07 %	136	0.041 %
Electric	53,841	0.12 %	11	0.003 %
Hybrid	236,710	0.51 %	12	0.004 %
Others	10,717	0.02 %	594	0.180 %
Total	46,474,594	100 %	329,559	100 %

In November 2018, the members of the European Parliament adopted strict targets to cut CO_2 emissions for trucks for the first time in history to spur the adoption rate of innovative and environmental-friendly trucks. By 2030, truck manufacturers must ensure that low and zero-emission trucks represent 20% of sales. In addition, new fleets' CO_2 emissions have to be reduced by 35% (European Parliament, 2018).

As a consequence, truck manufacturers are also investigating other eco-innovations to reduce emissions apart from alternative fuels such as "platooning" where at least two trucks, digitally coupled, drive on a single lane in close proximity what reduces aerodynamics and therefore fuel consumption and emissions. Digital data transmission and intelligent driving support systems such as automated braking are essential for safety reasons due to the short distances between trucks (Boysen, Briskorn and Schwerdfeger, 2018). However, according to Daimler Trucks, even under perfect platooning conditions fuel savings are less than expected and the

company is, therefore, stepping away from this technology (Daimler, 2019a). Hence, due to legal requirements, the expected increase in freight transport volume and a lack of alternatives, the adoption of alternative fuel-powered HDTs is required to reduce emissions per truck to contribute to a significant decrease of emissions from the transportation sector in Germany.

Our study contributes to research in two ways: First, we present the relative importance of various factors that affect the purchasing decision and operation of alternative fuel-powered HDTs in Germany. Second, we focus on different types of alternative fuels and drivetrains suitable for HDTs and present the main motivators and barriers when switching from diesel-powered HDTs to such environmental-friendly technologies. We also outline possible ways how to overcome the main barriers of each technology. The two research questions which guided the execution of this study are therefore:

What factors affect the purchasing decision and operation of alternative fuel-powered HDTs in Germany and which are the most relevant ones?

What alternative fuels and drivetrains are suitable for substituting diesel-powered HDTs, what are the main motivators and barriers to switching from diesel to those technologies and what are possible ways to overcome the main barriers?

We employed a Delphi study with industry professionals, researchers as well as consultants to debate both research questions. According to Von der Gracht (2012, p. 1526), the Delphi method is a "survey technique in order to facilitate an efficient group dynamic process. This is done in the form of an anonymous, written, multi-stage survey process, where feedback of group opinion is provided after each round". The remainder of this study is structured as follows: the next section summarizes the fundamental characteristics of the diffusion of eco-innovations, followed by outlining the methodological process utilized for the conducted Delphi study. Thereafter, we present and discuss the results of our study before concluding it.

2.2 The adoption process of eco-innovations

In December 2015, the climate Paris agreement was negotiated and adopted at the international climate summit and calls for comprehensive economic and societal changes. The legally binding target is to keep the increase in global average temperature well below two

degrees Celsius above pre-industrial levels. All 196 members of the United Nations Framework Convention on Climate Change agreed on a needed long-term approach to tackle climate change effectively (BMU, 2016).

Technological change including eco-innovation is needed for a successful transition to a GHG neutral society across all industry sectors. Technological change follows the Schumpeterian trilogy: (1) invention: generating new ideas, (2) innovation: the development of those ideas and (3) diffusion: spreading new technologies across its potential market (Stoneman and Diederen, 1994). According to Rennings (2000), an invention turns into an innovation when an improved good is first introduced to the market. Baregheh, Rowley and Sambrook (2009) note that the term innovation is of interest across a wide range of different disciplines, e.g. marketing, human resources or engineering, and argue that each discipline introduced definitions for innovation which align with the discipline's main paradigm. For instance, technologically related definitions focus on products related to new technologies such as utilizing fuel cells (FCs) to power electric vehicles. Rennings (2000) presents the definition of innovation as described in the Oslo Manual of the Organization for Economic Co-operation and Development (OECD) that is divided into organizational, process and product innovation. However, the author also criticizes this definition as "it does not explicitly distinguish between environmental and non-environmental innovations" (Rennings, 2000, p. 322).

Eco-innovation is a subset of innovations and is increasingly used to replace existing products in the economy (Wagner, 2008; Vigants *et al.*, 2016). Some eco-innovations are already at a mature stage, e.g. the photovoltaic market in Germany which can compete with traditional energy sources (Karakaya, Hidalgo and Nuur, 2014). The European Commission (EC) describes eco-innovation as "the key to Europe's future competitiveness" that helps "Europe optimise its growth potential while addressing our common challenges such as climate change" (EC, 2012). The field of eco-innovation has gained increasing attention in academic research in recent years (Hojnik and Ruzzier, 2016). However, previous studies do not agree on one common definition of eco-innovation. According to Kemp and Pearson (2007, p. 7) eco-innovation can be defined as the "production, assimilation or exploitation of a product, production process, service or management or business method that is novel to the organization (developing or adopting it) and which results, throughout its life cycle, in a

reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives". Horbach, Rammer and Rennings, (2012, p. 119) note that positive environmental effects of eco-innovations "can occur within the respective companies or through customer use of products or services". The Eco-Innovation Observatory (EIO) which aims to develop an integrated information source on eco-innovations states in its definition that eco-innovation "is the introduction of any new or significantly improved product" (EIO, 2018). Whether technology push factors (e.g. new environmental-friendly technologies) or market pull factors (e.g. image or preferences for eco-efficient products) are the main drivers for innovation has been a main discussion in innovation economics, but empirical evidence has proven that both push and pull factors are important. However, as those push and pull factors seem to be not strong enough, regulatory push such as environmental laws are needed for the successful introduction of new eco-innovations (Rennings *et al.*, 2006). Examples for such environmental-friendly innovations in practice presented by the EC are the use of FCs and hydrogen, organic farming or biogas production from household rubbish and food waste (EC, 2019a). While the public generally benefits from eco-innovations, firms that reduce their environmental burdens bear higher costs than their competitors that do not invest in environmental-friendly innovations (Rennings *et al.*, 2006). Rennings (2000) identified the double externality problem of eco-innovations which reduces the incentives for companies to invest in environmental-friendly innovations what leads to the importance of environmental policy instruments that help to increase the penetration rate of such innovations. According to Rennings *et al.* (2006), financial support from innovation policy is therefore necessary when inventing a new product or introducing it to the market to initiate first pilot tests. Environmental policy is also needed during the diffusion phase of an eco-innovation for internalizing external costs by competitors that offer non-ecological products. Such peculiarities lead to a comparably slow diffusion of eco-innovations (Kijek, 2015).

Research on the diffusion of innovations aims to identify the factors that influence the adoption of new technologies. One frequently cited theory related to the diffusion of innovations was described by Rogers (2003, p. 5) who defines diffusion as "the process by which an innovation is communicated through certain channels over time among the members of a social system". The diffusion of innovations theory can be applied to various

innovations, including eco-innovations (Kijek, 2015). For instance, Roger's theory has been used by Plötz, Gnann and Wietschel (2014) to model the market diffusion of electric vehicles in Germany. According to Karakaya, Hidalgo and Nuur (2014), Roger's definition contains the four main pillars of innovation diffusion, namely innovation, communication channels, time and the social system. There are different means to share information between individuals, however, interpersonal face-to-face communication usually seems to be more efficient than other communication channels such as television or the internet when convincing someone to adopt an innovation. Time is also an important aspect to test how long it takes for an individual to decide whether to adopt or reject an innovation. Furthermore, the diffusion of innovation will be affected by the social structure of a system through opinion leaders or social consequences (Karakaya, Hidalgo and Nuur, 2014). According to Rogers (2003), adopters of innovations can be divided into five categories which correspond to the different phases of adoption during market development: (1) innovators, (2) early adopters, (3) early majority, (4) late majority, and (5) laggards. The diffusion of innovation process usually generates an S-shaped curve which starts with a slow diffusion in the initial stage, followed by a recovery period and ends in a saturation phase where complete adoption is reached (Kijek, 2015).

2.3 Research methodology

2.3.1 Delphi method

Sponsored by the United States Air Force, the Delphi method was first applied by the U.S. RAND Corporation in the 1950s within the scope of a military project (Dalkey and Helmer, 1963). The technique mostly deals with complex problems and helps to structure the group communication process (Linstone and Turroff, 1975). The original aim of the Delphi technique was "to obtain the most reliable opinion consensus of a group of experts by subjecting them to a series of questionnaires in-depth interspersed with controlled feedback" (Dalkey and Helmer, 1963, p. 458).

There are four main characteristics of the Delphi methodology that usually remain the same. *Anonymity* of the participating experts will be guaranteed by the facilitator who is coordinating the process. Delphi studies are executed in a *series of rounds* where the facilitator summarizes

the feedback of the participants and provides it as additional information for the following round. The third characteristic is *controlled feedback* since the facilitator statistically analyzes the input of the experts after each round and decides on the provision of the feedback. The *statistical group response* is usually shown by measures of dispersion or central tendency such as the median and mean of the responses (Von der Gracht, 2012).

We conducted a traditional Delphi study where the facilitator designs a survey and receives individual expert input over a minimum of two rounds (one assessment round and one revision round) what allows the expert panel to reassess given replies of the previous round based on the aggregated group opinion (Gary and von der Gracht, 2015). Recent attempts have also used internet-based real-time Delphi studies where statistical group response is calculated immediately and presented back to the expert panel (Gordon and Pease, 2006). Gnatzy *et al.* (2011) compared the results of both traditional and internet-based real-time Delphi studies and could not find significant differences in the robustness of empirical results.

Certain aspects need to be addressed carefully for all kind of Delphi studies. Murray (1979) investigated some important criticisms that have been raised against the technique in the literature such as the selection of experts and a changing panel membership. Besides, respondents are usually not equally expert in all areas touched upon in a survey. Moreover, a lack of stability in the Delphi panel can be another problem, for instance, through the addition of new experts who have not participated in previously conducted rounds (Murray, 1979). The rigorous selection of experts is of great importance when it comes to the final Delphi panel composition to ensure that chosen candidates have deep knowledge in the investigated field and are therefore qualified to participate in the study (e.g. Landeta, 2006; Spickermann, Zimmermann and von der Gracht, 2014). We have selected the Delphi technique as the method of choice for several reasons. First, the Delphi method relies on the findings of an expert panel whereas other methods trust in single opinions which can be misinformed and incorrect. Second, refining is possible in Delphi studies as it allows experts to see the replies of the other panel members. Third, some studies rely on open roundtable discussions with experts, but those discussions will be usually highly influenced by dominant participants what leads to conformity rather than objective results (Ogden *et al.*, 2005). Fourth, other crowdsourcing techniques focus on interviewing a large sample size including laypersons. The Delphi technique, on the other hand, is targeting a limited group of experts from a specific

field and has proven its validity in many different research contexts (Förster and von der Gracht, 2014). For instance, Delphi "has repeatedly been used to investigate factors influencing decision-making on a specific issue, topic or problem area in supply chain management" (Kembro, Näslund and Olhager, 2017, p. 79) such as the study by Maccarthy and Atthirawong (2003) dealing with factors that affect location decisions in international operations. Lastly, due to financial and time constraints, it is difficult to bring in all experts for a face-to-face meeting as they may be located in different geographical regions (Richardson, Leeuw and Dullaert, 2016). Besides, the Delphi method has been applied in previous studies to assess the implications of various (eco-) innovations such as solar power (Hsueh, 2015), 3D printing (Jiang, Kleer and Piller, 2017) or big data applications (Roßmann *et al.*, 2018).

Following the process of Von der Gracht and Darkow (2010), Fig. 1 illustrates the different phases of the conducted Delphi study. First, we identified factors affecting the purchasing decision and operation of alternative fuel-powered HDTs in Germany as well as alternative fuels and drivetrains suitable for HDTs. The second phase included the design of the first survey, pretests and the careful selection of potential experts. Third, panelists were contacted and completed the survey during the first Delphi round and fourth, statistical group response of the first round was analyzed as part of the interim analysis. In addition, we designed the second survey and pretested it. Fifth, experts were asked to revise the results of the first round based on provided feedback in the second survey. Lastly, statistical group response of the second round was analyzed and the study concluded. The different phases will be further described in the following sections.

Figure 1: Delphi process phases (based on Von der Gracht and Darkow, 2010)

2.3.2 Identification of factors and alternative fuels

We used a similar Delphi approach as Maccarthy and Atthirawong (2003) who identified factors affecting location decisions in international operations as well as Richardson, Leeuw and Dullaert (2016) who assessed factors affecting global inventory prepositioning locations

in humanitarian operations. To establish a comprehensive set of arguments, we collected secondary data from various scientific studies to identify factors that affect the purchasing decision and operation of alternative fuel-powered HDTs in Germany. Following the process for factor identification utilized in the Delphi study by Kwiatkowski and Chinowsky (2017), we used different keywords for our search such as "electric trucks", "low-emission vehicles" or "alternative fuels" to find appropriate studies. We tried to focus on research concerning trucks only and purposefully kept the search narrow given the specific research field on alternative fuel-powered HDTs. The asterisk, a standard Boolean method, was also used to search for all words containing the root term, for instance in the case of "adopt*". Papers were excluded if they did not include any factors that hinder or spur the adoption of low-emission vehicles.

In January 2018, identified factors were checked for completeness by five logistics and alternative fuels experts from a German multinational car manufacturer who selected the most promising alternative fuels and drivetrains for HDTs, too. Neither the car manufacturer nor any of its subsidiaries produce trucks what precludes potential biases in any direction as there is no interest in promoting or excluding specific technologies. All participants work on the manufacturer's "Green Logistics Strategy" which focuses on the successful transition to a GHG neutral supply chain. In cooperation with truck manufacturers, infrastructure experts and logistics service providers (LSPs), the candidates have already successfully implemented battery electric as well as natural gas HDTs in the company's supply chain. In addition, several pilot tests, as well as research projects concerning alternative fuel-powered HDTs were set up to further reduce emissions. Summarized, we evaluate the participants as a knowledgeable and sound group of experts that is well connected to truck manufacturers, LSPs and other key market players.

Previously identified factors were then allocated to one of five major categories defined in cooperation with the same group. Following Okoli and Pawlowski (2004), a grouping of factors into major categories will not be for analysis and was done for presentation purposes only. Apart from evaluating identified factors, a second component of the two face-to-face workshops held in January 2018 was the selection of promising alternative fuels and drivetrains that are suitable for HDTs. Selected technologies were chosen by the participants based on three pillars: (1) the current or foreseeable market availability of the technology, (2)

the potential to reduce emissions from transport and (3) do not include any type of diesel (engine). Accordingly, "biodiesel" variants such as hydrotreated vegetable oil (HVO) or hybrid HDTs which combine conventional diesel engines with electric propulsion systems were excluded.

2.3.3 Selection of experts

Thereafter, we started identifying potential experts for the final panel. There exists no specific rule for the ideal number of Delphi experts in academic literature (Giunipero, Hooker and Denslow, 2012). However, Akkermans *et al.* (2003) describe that an essential characteristic of Delphi studies is the participation of at least 20 experts. On the other hand, Ogden *et al.* (2005) argue that studies should typically utilize up to 30 experts based on the finding that just little additional information will be generated by a larger expert panel. The aim of this Delphi study was to elicit knowledge from a heterogeneous group of experts with a deep knowledge about alternative fuel-powered HDTs and a good overview of the German truck market what leads to a rather small group of potential experts. As previously explained, the thorough selection of experts is an essential part of each Delphi study to ensure data reliability (Welty, 1972; Spickermann, Zimmermann and Von der Gracht, 2014). To avoid misleading results of a homogenous panel, previous research recommends to include a diverse set of viewpoints (Spickermann, Grienitz and Von der Gracht, 2014). Förster and Von der Gracht (2014) assessed the Delphi panel composition for strategic foresight and compared Delphi panels based on external and company-internal participants. The authors argue that previous research has shown that a lack of diversity among Delphi respondents could lead to biased results as respondents in homogenous Delphi panels are likely to have similar viewpoints. Förster and Von der Gracht (2014) focus on diversity that arises from selecting respondents from different institutions and conduct two identical surveys with two Delphi panels: the first panel comprises of managers from one large company whereas the participants from the second panel came from the company environment including academics. The authors conclude that internal Delphi panels should be utilized to discuss company-internal topics whereas external panels should be preferred when numerous perspectives are desired (Förster and von der Gracht, 2014). Consequently, we followed the approach of assembling a heterogenous Delphi panel and identified truck manufacturers, LSPs, infrastructure experts, consultants and

researchers as the five most important stakeholder groups. To increase the reliability of our results, particularly in an emerging and innovative field such as alternative fuel-powered HDTs, individuals were targeted based on a set of strict and objective multi-perspective criteria, predefined for each expert group (Nowack, Endrikat and Guenther, 2011; Kwiatkowski and Chinowsky, 2017). First, all potential experts need a minimum industry experience of five years. Second, contacted experts from manufacturers work in the field of alternative drivetrains at the largest European truck manufacturers. Third, we invited experts from LSPs that have or had alternative fuel-powered vehicles in operation. Identified experts were either involved in the purchasing decision or support the adoption of additional low-emission vehicles in the company to reduce fleet emissions. Fourth, we invited infrastructure experts from European oil and gas companies that either work on alternative fuels or published studies on low-emission drivetrains. Fifth, researchers were contacted if they have published at least two studies on alternative fuels suitable for HDTs. Lastly, consultants were targeted due to previous projects or publications focusing on alternative fuel-powered trucks. In addition, we followed Brown and Helmer (1964), Best (1974) and Bijl (1992) and included the following self-assessment question in the first round to further increase data reliability: *"How would you rank your level of expertise on alternative fuel-powered HDTs?"*.

2.3.4 First Delphi round

Reliability and content of the survey were assessed before the survey was sent to the experts (Von der Gracht and Darkow, 2010). A pilot study was therefore conducted after completion of the survey design to ensure completeness and plausibility. In February 2018, we invited the previously introduced workshop participants to pre-test the first survey of our study as they are well connected to all identified stakeholder groups and are thus able to articulate diverse viewpoints. Recommended changes were discussed and incorporated in the survey. The five respondents of the pilot study did not participate in the final Delphi rounds.

The 14-page-long survey, as well as an information sheet explaining the scope of research and methodology used were sent to the identified experts mid-March 2018 via email. Detailed instructions on how to complete the survey were given on the first page of the survey.

We followed a similar study design as Maccarthy and Atthirawong (2003) and divided the main body of the survey in Part A and Part B. The former focused on identified factors and their relative importance when purchasing and operating alternative fuel-powered HDTs in Germany. Part B, on the other hand, focused on motivators and barriers when switching from diesel-powered HDTs to alternative fuels but also on possible ways how to overcome the main barriers of each technology.

In Part A, a seven-point Likert scale from (1) unimportant to (7) extremely important was used to measure the importance of each factor. Besides, experts had the opportunity to leave additional comments for further insights below each major category. Part B of the survey was divided into four sections. Each section covered one of the identified alternative fuels suitable for HDTs. We provided a short definition of each technology to avoid misunderstandings followed by three open-ended questions to generate a list of arguments as described by Okoli and Pawlowski (2004). Maccarthy and Atthirawong (2003) also argue in their Delphi study that open-ended questions allow the panel members to provide and express their opinions independently. The first and second question of each technology section dealt with motivators and barriers to switching from diesel-powered HDTs to its alternative fuel-powered counterpart. The third question asked the panelists to provide possible ways how to overcome the described barriers of the technology. We provided text boxes for further comments below each technology section.

2.3.5 Interim analysis and second Delphi round

Completed surveys of the first round were received back from the experts at the beginning of April 2018. During the interim analysis, both quantitative and qualitative data were evaluated. In the case of Part A, we used descriptive statistics to get a first estimation of consensus and relative importance. Following the approach of Okoli and Pawlowski (2004) for open-ended questions in Delphi studies, we evaluated and clustered received comments of the first survey in Part B to avoid identical aspects in the second Delphi round. For instance, we aggregated comments concerning a higher purchasing price of alternative fuel-powered HDTs compared to diesel-powered vehicles as "higher purchasing price" and presented them in the barrier section of the respective technology. By doing so, we reduced 493 collected qualitative

arguments from the first round to 119 in the second survey. The consolidated lists of motivators, barriers, and solutions for each technology were then fed back in round two of the Delphi study. Panelists could leave comments in the second survey to verify that we have correctly interpreted their responses (Okoli and Pawlowski, 2004).

The second 33-page-long survey was sent via email to the experts in mid-April 2018 in order to reassess responses of the first round. We followed Okoli and Pawlowski (2004) and provided both an exact copy of their first survey and the second survey attached to the invitation email. However, we did not include the personal responses of the first round within the second survey as our pretest experts commented that it is more likely to give the same reply instead of scrutinizing the opinion of the other participants. The first page included specific instructions with a short explanation for the second round. In Part A, we followed the identical structure as in the first round but added bar charts to visualize the statistical group response and distribution of replies. We also colored the calculated median of round one responses for each factor (Tapio, 2002). No additional statistics such as the interquartile range (IQR) were fed back to the panelists as pretests have indicated no additional benefits. In Part B, the complete consolidated lists of motivators, barriers, and solutions for each technology were presented to the participants. The experts were then asked to select the three most important motivators and barriers of each technology as well as the three most promising ways on how to overcome those barriers.

2.3.6 Final analysis and termination of Delphi study

The completed surveys of the second round were received back at the beginning of May 2018. A critical point of each Delphi study is the definition of a stopping criterion as Delphi facilitators can terminate a study due to budget or time constraints (Von der Gracht, 2012). In order to provide a statistically proven criterion, most researchers choose expert consensus as the final aim of their study although a certain level of agreement alone seems insufficient to terminate a Delphi study (Von der Gracht, 2012). Dajani, Sincoff and Talley (1979) argue that consensus measurement is useless if stability of received expert responses was not reached. Thus, we tested for both consensus and stability of replies in Part A. Stability can be concluded if consistency of replies was reached between successive rounds (Dajani, Sincoff

and Talley, 1979). As recommended by Von der Gracht (2012), stability of the replies was tested by changes in the coefficient of variation (CV). The CV is the ratio of the standard deviation of an expert opinion on a specific factor to the corresponding mean. To measure stability, the absolute CV change for each factor was calculated by subtracting the CV results of round one from round two (Kalaian and Kasim, 2012). A maximum threshold value of 0.1 was used in previous Delphi research and found to be a suitable value for reached stability (Kwiatkowski and Chinowsky, 2017). Due to its robustness, the IQR was chosen to test the level of consensus between the panelists (Murphy *et al.*, 1998). The IQR "is the measure of dispersion for the median and consists of the middle 50% of the observations" (Von der Gracht, 2012, p. 1531). It is a widely accepted method and was used in previous Delphi studies (e.g. Von der Gracht and Darkow, 2013; Spickermann *et al.*, 2014). On a seven-point Likert scale, a maximum IQR of 1.0 is recommended as a suitable indicator for reached consensus (De Vet *et al.*, 2005).

Feedback from experts indicated that it would be difficult to achieve a high response rate for several additional Delphi rounds due to personal time constraints. As a result of the high level of stability and consensus in Part A and the ability to draw relevant conclusions from Part B, we decided to terminate the study after two rounds to avoid research fatigue within the panel. However, individual feedback, the high participation rate and the number of written comments can be interpreted as an indicator for the high level of interest in the investigated research field. Melander (2018) examined how the Delphi technique has been used in 20 transport studies and found out that most authors also terminated their Delphi study after two rounds.

2.4 Results and discussion

2.4.1 Delphi expert panel

Based on the set of described criteria, we identified 55 experts and invited them to participate in our study via email. 23 experts participated in the study what corresponds to a participation rate of 41.8%. The final panel consisted of six experts from the largest European truck manufacturers, seven experts from LSPs, one infrastructure expert from a European oil and gas company, five consultants and four researchers. We included one expert per company or

institution to ensure a diverse set of viewpoints and to preclude biased results in any direction. All panel members are male, and the industry experience ranges from six to 37 years with a median of 20 years. A summary of participating experts including position is presented in Table 2.

Table 2: Delphi expert panel

Expert Group	Position	Industry Experience (years)
Truck Manufacturer	Head of Alternative Fuels and Drivetrains	33
Truck Manufacturer	Head of Environment and Innovation	22
Truck Manufacturer	Head of Foresight	37
Truck Manufacturer	Manager Sustainable Transport Solutions	10
Truck Manufacturer	Natural Power Expert	13
Truck Manufacturer	Senior Manager - Product Engineering Alternative Drivetrains	20
LSP	CEO	35
LSP	CEO	18
LSP	CEO Deputy	20
LSP	Corporate Director	25
LSP	Head of Business Development	18
LSP	Manager Green Logistics	20
LSP	Manager Health, Safety & Environment	7
Infrastructure	Senior Manager - Global Solutions	35
Consulting	Area Director Industrial Goods and Services	20
Consulting	Head of Automotive Business Unit	8
Consulting	Deputy Head of Renewable Energy and Mobility	10
Consulting	Partner - Automotive Strategy	15
Consulting	Senior Consultant	33
Research	Professor - Alternative Fuels and Drivetrains	25
Research	Professor - Transport and Mobility	20
Research	Project Manager - Transport and Mobility	6
Research	Team Lead - Commercial Transport	27

Following Brown and Helmer (1964), Best (1974) and Bijl (1992), we included the following self-assessment question in the first round survey to ensure data reliability: *"How would you rank your level of expertise on alternative fuel-powered HDTs?"*. On a five-point Likert scale, eight participants (34.8%) ranked their expertise as (5) extremely high, ten (43.5%) as (4) high and

five (21.7%) as (3) basic. Accordingly, none of the panelists answered the self-assessment question below basic expertise. One expert did not participate in the second round which equals a dropout rate of 4.3%. Previous research with a sample of 24 Delphi studies shows an average dropout rate of 18% between the first two rounds (Nowack, Endrikat and Guenther, 2011) what signals that participating experts were overall satisfied with the survey design and the content of our study.

2.4.2 Part A: Factors affecting the purchasing decision and operation

Secondary data from different scientific papers was collected to identify factors that affect the purchasing decision and operation of alternative fuel-powered vehicles. Our search resulted in 66 English language scientific papers which were reviewed to identify factors that drive the adoption or aversion of alternative fuel-powered vehicles. As research on low-emission heavy-duty vehicles (HDVs) is rather limited, previously published papers tend to investigate passenger vehicles mainly. Summarized, we identified 34 factors in twelve academic papers, seven of them focusing on alternative fuel-powered passenger cars and three on HDVs. Two papers do not specify what type of vehicle they are investigating. Some factors presented were only found in scientific papers related to passenger cars but seem to be applicable also for HDTs, for instance, "reliability" (Ozaki and Sevastyanova, 2011) or "refueling time" (Junquera, Moreno and Álvarez, 2016). Identified factors were allocated to one of five major categories defined in cooperation with the workshop participants: *costs*, *socioeconomic factors*, *environmental factors*, *daily practicability* and *political factors*. As previously described, the grouping of factors into major categories was done for presentation purposes and will not be analyzed. The set of identified factors, major categories and corresponding references are summarized in Table 12 in the appendix.

Using a seven-point Likert scale, participants were asked to rate to what extent each factor affects the purchasing decision and operation of alternative fuel-powered HDTs in Germany. The results of both Delphi rounds are summarized in Table 3, indicating the IQR for consensus measurement and CV change for stability measurement. We use the mean score to analyze the relative importance of each factor and provide the median as additional information to the reader.

Table 3: Factors affecting the adoption of alternative fuel-powered HDTs in Germany

	Round 1 (n = 23)				Round 2 (n = 22)						
Factor	**IQR**	**CV**	**Median**	**Mean**	**IQR***	**CV**	**Median**	**Mean**	**CV change****	**Con-sensus**	**Sta-bility**
1. Current fuel costs	1.00	0.21	6.00	6.04	1.00	0.12	6.00	6.27	0.09	Yes	Yes
2. Future trend in fuel costs	1.50	0.28	7.00	5.87	1.00	0.19	7.00	6.27	0.10	Yes	Yes
3. Service and maintenance costs	1.00	0.17	5.00	5.35	1.00	0.13	5.00	5.32	0.04	Yes	Yes
4. Expenses for repairs	1.00	0.22	5.00	5.22	0.00	0.14	5.00	5.14	0.08	Yes	Yes
5. Purchasing price	2.00	0.18	6.00	5.83	1.75	0.15	6.00	5.91	0.03	No	Yes
6. Taxes and insurance	1.50	0.37	4.00	4.30	1.75	0.28	4.00	4.09	0.09	No	Yes
7. Depreciation/ Resale value	1.00	0.21	6.00	5.48	1.00	0.15	6.00	5.68	0.06	Yes	Yes
8. Being a trendsetter in environmental-friendly technologies	1.50	0.33	5.00	4.48	1.00	0.29	4.00	4.50	0.04	Yes	Yes
9. Being part of socially responsible activities (marketing/ reputation)	1.50	0.32	5.00	4.57	1.00	0.24	5.00	4.73	0.09	Yes	Yes
10. General excitement about new technologies/ innovations	1.00	0.33	5.00	4.48	1.00	0.26	5.00	4.73	0.07	Yes	Yes
11. Greenhouse gas emissions	1.50	0.28	6.00	5.39	1.00	0.21	6.00	5.64	0.07	Yes	Yes
12. Noise emission	1.00	0.28	5.00	5.04	1.00	0.17	6.00	5.41	0.11	Yes	No
13. Ecological impact of truck manufacturing and recycling	2.50	0.44	3.00	3.87	2.00	0.38	3.00	3.82	0.06	No	Yes
14. Well-to-Tank emissions	3.50	0.46	5.00	4.30	2.75	0.40	4.00	4.14	0.06	No	Yes
15. Tank-to-Wheel emissions	2.00	0.34	6.00	5.17	0.75	0.20	6.00	5.59	0.14	Yes	No
16. Well-to-Wheel emissions	1.00	0.32	6.00	5.17	1.00	0.24	6.00	5.45	0.08	Yes	Yes
17. Reliability	0.00	0.06	7.00	6.83	0.00	0.03	7.00	6.95	0.03	Yes	Yes
18. Refueling time	1.00	0.18	5.00	5.43	1.00	0.15	5.50	5.50	0.04	Yes	Yes
19. Maximum vehicle driving range	2.00	0.15	6.00	5.96	0.00	0.12	6.00	6.00	0.03	Yes	Yes
20. Safety features	1.50	0.19	5.00	5.35	1.00	0.18	6.00	5.50	0.02	Yes	Yes
21. Maximum payload capacity	2.00	0.18	6.00	6.00	1.75	0.14	6.00	6.14	0.05	No	Yes
22. Brand/model of vehicle	1.00	0.30	4.00	4.35	1.00	0.22	4.00	4.36	0.08	Yes	Yes
23. Service quality of manufacturer	1.50	0.13	6.00	6.04	0.75	0.10	6.00	6.14	0.02	Yes	Yes
24. Fueling/charging infrastructure	1.00	0.11	7.00	6.57	0.00	0.06	7.00	6.82	0.05	Yes	Yes
25. Manufacturers' warranties	1.50	0.16	6.00	5.87	0.00	0.10	6.00	6.09	0.06	Yes	Yes
26. Vehicle design	2.00	0.40	3.00	3.04	1.50	0.39	3.00	3.32	0.01	No	Yes
27. Driver comfort	1.00	0.16	5.00	5.48	1.00	0.21	5.50	5.41	-0.05	Yes	Yes
28. Performance/ drivability	0.50	0.13	6.00	5.87	0.00	0.10	6.00	6.00	0.03	Yes	Yes

29. Level of extra equipment	2.00	0.29	5.00	4.83	0.75	0.21	5.00	4.91	0.08	Yes	Yes
30. Fuel specifications in tenders	2.00	0.27	6.00	5.61	1.00	0.17	6.00	6.00	0.10	Yes	Yes
31. Possibility to enter low-emission zones	1.00	0.15	6.00	6.17	1.00	0.14	7.00	6.36	0.01	Yes	Yes
32. Possibility to enter low-noise zones	1.50	0.17	6.00	5.91	0.75	0.12	6.00	6.09	0.05	Yes	Yes
33. Financial incentives when purchasing/ operating an alternative fuel-powered truck	1.50	0.18	6.00	6.00	1.00	0.12	6.00	6.27	0.06	Yes	Yes
34. Independence of oil producers	2.00	0.50	3.00	3.39	2.00	0.47	3.00	3.27	0.03	No	Yes

* Consensus reached if interquartile range (IQR) of maximum 1.0 (De Vet *et al.*, 2005)
** Stability reached if absolute coefficient of variation (CV) difference between round 1 and round 2 of maximum 0.1 (Kwiatkowski and Chinowsky, 2017)

2.4.2.1 Stability of results and consensus measurement

Table 3 shows that all but two factors (94.1%) met the predefined threshold value of 0.1 for stability after the second round. Stability of responses was particularly high for the following three factors: *safety features* (0.02), *vehicle design* (0.01) and the *possibility to enter low-emission zones* (0.01). We calculated a CV change of 0.11 for *noise emission* and 0.14 for *Tank-to-Wheel emissions*, thus, only 0.01 and 0.04 higher than the defined maximum value.

The development of consensus measurement based on the IQR, presented in Table 3, indicates that 14 factors (41.2%) reached consensus after the first round as the IQR of those factors was below the recommended threshold value of 1.0 for the utilized seven-point Likert scale. Results of round two show that three of those 14 factors that had already reached consensus after the first Delphi round, could further improve the reached level of agreement. Because of this, controlled feedback and statistical group response likely led to a convergence of experts' opinions. In total, consensus was attained for 27 factors (79.4%) after the second round. A high level of consensus represented by an IQR of 0.0 could be reached for *expenses for repairs*, *reliability*, *maximum vehicle driving range*, *fueling/charging infrastructure*, *manufacturers' warranties* and *performance/drivability*. On the other hand, the following factors could not reach consensus: *purchasing price*, *taxes and insurance*, *ecological impact of truck manufacturing and recycling*, *well-to-tank emissions*, *maximum payload capacity*, *vehicle design* and *independence of oil producers*.

2.4.2.2 Relative importance

We follow a similar way as Maccarthy and Atthirawong (2003) as well as Richardson, Leeuw and Dullaert (2016) in the way of presenting the relative importance of factors, as the methodology used in both Delphi studies is most aligned with ours.

According to the replies of the expert panel, *reliability* (6.95), *fueling/charging infrastructure* (6.82), *possibility to enter low-emission zones* (6.36), *current fuel costs* (6.27) and *future trend in fuel costs* (6.27) affect the purchasing decision and operation of alternative fuel-powered HDTs in Germany the most. The factors rated with least importance are *independence of oil producers* (3.27), *vehicle design* (3.32), *ecological impact of truck manufacturing and recycling* (3.82), *taxes and insurance* (4.09) as well as *well-to-tank emissions* (4.14).

Fig. 2 to 6 below summarize the results for each major category and present the relative importance per factor in decreasing order.

Cost Factors: Fig. 2 shows the relative importance of factors related to the major category *cost*. Both *future trend in fuel costs* (6.27) and *current fuel costs* (6.27) are the most important factors within the category. Popp *et al.* (2009) also describe that relative fuel prices are relevant to customers and even more for those who are buying low-emission vehicles. In contrast to our results, Knez, Jereb and Obrecht (2014) reported that the vehicle purchasing price is most important for consumers when purchasing a new car. However, a participant of our study explained the relevance of HDT fuel costs by indicating that "fuel costs account for the largest share of annual truck costs and are therefore the most relevant cost factor". The same participant added "that capital costs (including purchasing price and vehicle resale value) follow fuel costs. Service, maintenance and insurance costs account for a relatively small share of the total-cost-of-ownership and are therefore less important". According to the KBA, the average annual mileage for passenger vehicles in 2017 was around 14,000 km but almost 97,000 km for HDT truck tractors (KBA, 2018b). We therefore assume that the importance of fuel costs is related to the average annual driving range of HDTs. Other panelists indicated that factors directly impacting the total-cost-of-ownership (TCO) of a truck are typically most important to customers. The attractiveness of alternative fuels in the U.S. trucking industry was already analyzed in the 1990s by Parker, Fletchall and Pettijohn (1997) who concluded that utilizing alternative fuel-powered trucks needs to be most importantly cost-efficient.

Sierzchula (2014) argues that firms are more likely to purchase low-emission vehicles despite higher purchase costs as they are focusing on the overall costs which can be reduced through decreasing operating expenses.

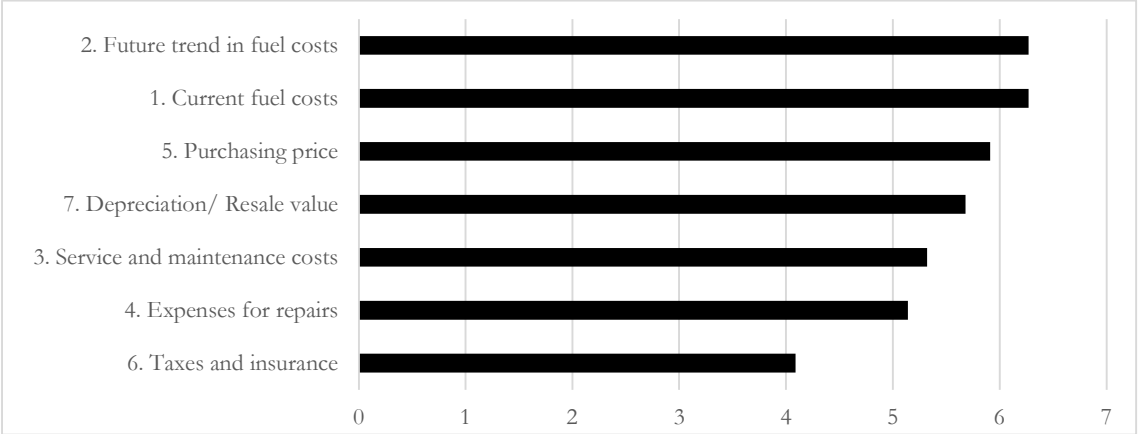

Figure 2: Relative importance of cost factors

Socioeconomic Factors: The relative importance of the three presented socioeconomic factors displayed in Fig. 3 were ranked between 4.50 and 4.73 and can be therefore considered as comparably less important criteria. One Delphi expert noted that such factors are not as relevant as others since "logistics service providers define themselves because of price and reliability" in the industry. One participant argued that a positive brand image can often be created by operating just a few alternative fuel-powered trucks, "but operating a 100% low-emission fleet is a totally different thing". This statement corresponds to the results of Sierzchula (2014) who found out that some firms bought electric vehicles for greenwashing the organization's image only although "improving the organization's public image" (Sierzchula, 2014, p. 130) is one of the factors most often identified why fleet managers decide to buy electric vehicles. Nevertheless, there are also consumers who purchase low-emission vehicles to reduce their own ecological footprint which is their main purchasing motivator (Ozaki and Sevastyanova, 2011).

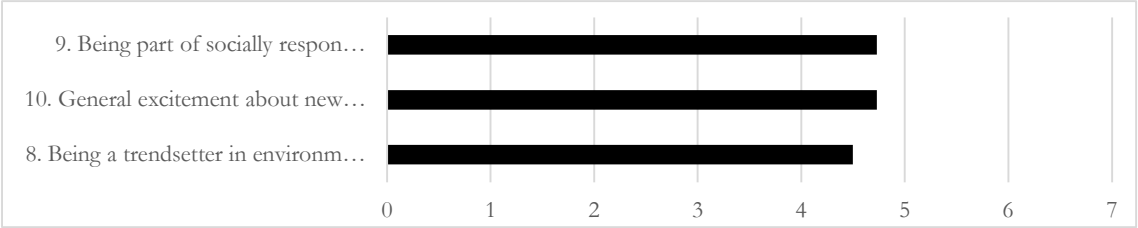

Figure 3: Relative importance of socioeconomic factors

Environmental Factors: Fig. 4 summarizes the relative importance of environmental factors when purchasing and operating an alternative fuel-powered HDT in Germany. Results show that *greenhouse gas emissions* (5.64), *Tank-to-Wheel emissions* (5.59) as well as W*ell-to-Wheel emissions* (5.45) were ranked as the most important factors. One expert noted that *Well-to-Wheel emissions* need to be analyzed to ensure zero emission trucking in the future. *Well-to-Wheel emissions* are divided into *Well-to-Tank emissions*, "accounting for the energy expended and associated emissions to deliver the finished fuel in the fuel tank" and *Tank-to-Wheel emissions* "that include the final conversion of the fuel in the vehicle" (Alamia *et al.*, 2016, p. 446). However, Alamia *et al.* (2016) argue that an international standard for analyzing *Well-to-Wheel emissions* does not exist yet. A Delphi participant stated that "*environmental factors* such as *noise emissions* need to be carefully considered when having direct impact on the transport itself, e.g. in case of night-time deliveries or transports within low-emission zones". Another expert noted that a standard for measuring street-level noise such as the Dutch PIEK certification does not exist yet in Germany. *Well-to-Tank emissions* (4.30) and the *ecological impact of truck manufacturing and recycling* (3.82) were evaluated with the least importance in the environmental category. Two Delphi panelists mentioned that margins in the road freight industry are decreasing and environmental factors need to be economically feasible, too. Knez, Jereb and Obrecht (2014) show that lower running costs are one main motivator when purchasing a new vehicle whereas reduced emissions are often evaluated as a bonus, but not a top priority.

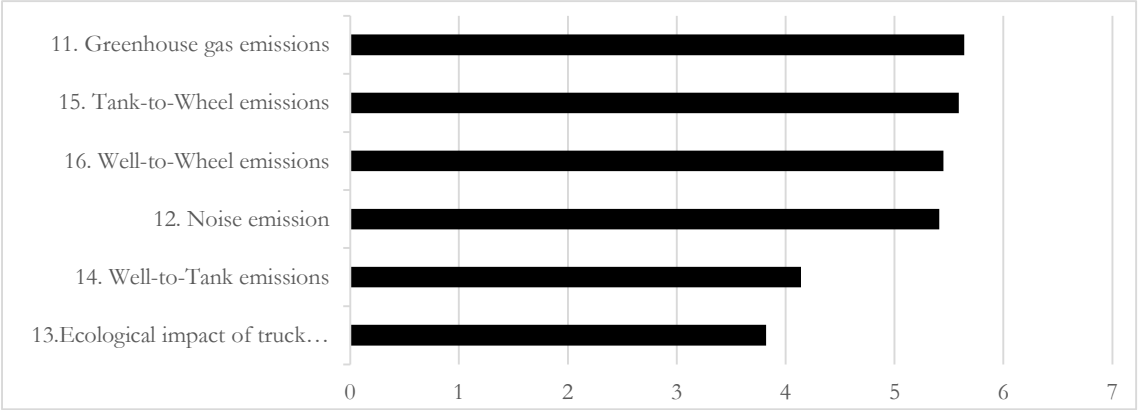

Figure 4: Relative importance of environmental factors

Daily Practicability: Thirteen factors were allocated to *daily practicability* and are presented in Fig. 5. As previously described, *reliability* (6.95) and the *fueling/charging infrastructure* (6.82) were evaluated as the factors with the highest relative importance. The latter will be extensively discussed in Part B as it was mentioned as one of the main barriers for the identified technologies suitable to substitute diesel-powered HDTs. One expert explained that the *reliability* of trucks is essential to ensure on-time deliveries and to avoid costly fines due to delays. The importance of the vehicle's *reliability* was highlighted by another expert who summarized that "*reliability* is key to avoid that customers switch to one of our competitors". The *maximum payload capacity* is strongly dependent on a truck's main field of application as just specific operations require the maximum payload capacity as commented by one participant and are rather limited in length, height or width. The *vehicle design* (3.32) was rated as one of the least important criteria when purchasing and operating an alternative fuel-powered HDT in Germany. Contrary to commercial vehicles, "Style/Appearance/Color" was evaluated in the study of Knez, Jereb and Obrecht (2014) as one of the most important aspects of private consumers when purchasing a low-emission car. One expert noted that "factors such as *vehicle design* or a truck's *brand* are important to customers, too, but ultimately secondary compared to other criteria". However, another Delphi expert referred to the current truck driver shortage in Europe and argued that it is certainly "important to have a great working environment for the driver".

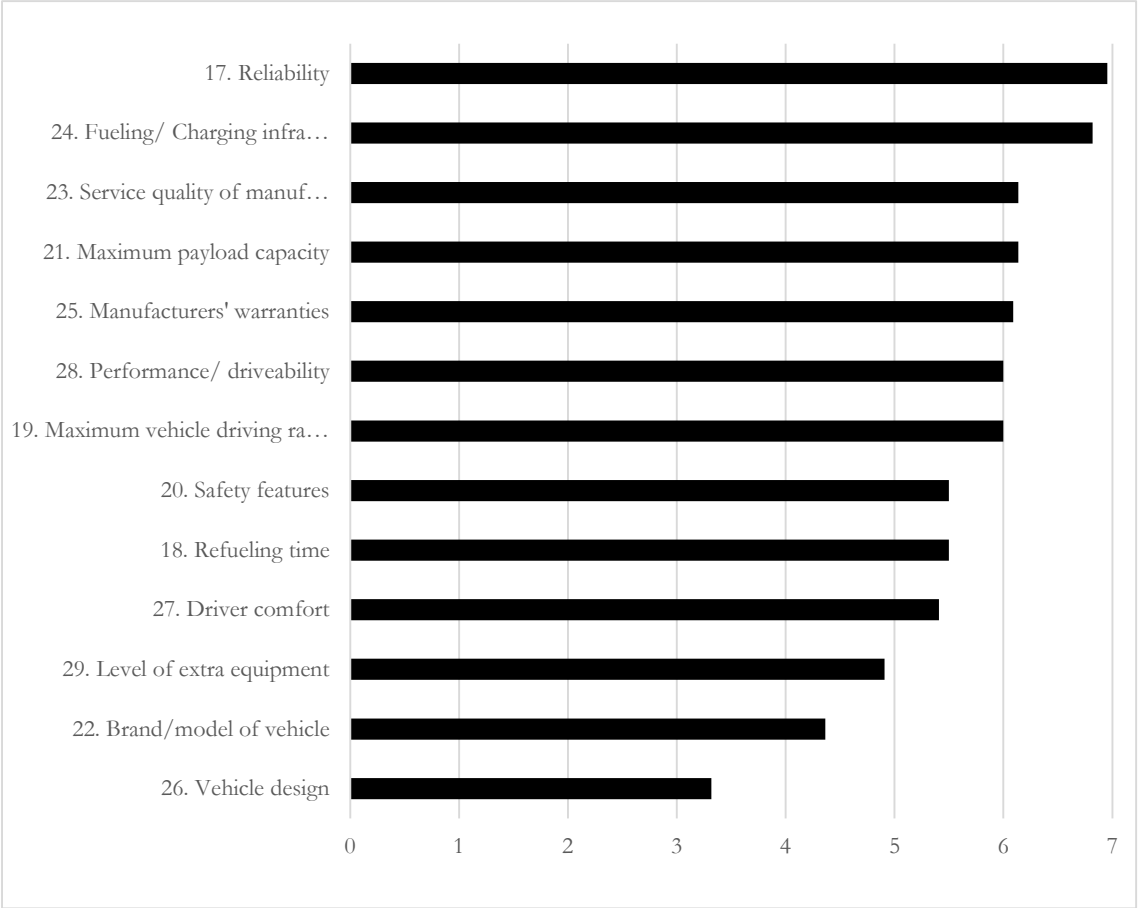

Figure 5: Relative importance of factors related to daily practicability

Political Factors: Fig. 6 outlines the results of the five identified *political factors*. The most important criterion when purchasing and operating an alternative fuel-powered HDT is *the possibility to enter low-emission zones* (6.36). One panel member referred to the decision of the German Federal Administrative Court in Leipzig and commented that factors such as the *possibility to enter low-emission zones* get relevant if political guidelines in Germany or Europe are getting stricter. In February 2018, hence, before the first Delphi round, the Court in Leipzig decided that diesel vehicles can be banned from German city centers to reduce harmful emissions (Bundesverwaltungsgericht, 2018). Results by Parker, Fletchall and Pettijohn (1997) show that truck operators switch to alternative fuels in case of cost savings or if changes in legislation force a conversion to low-emission trucks. This thought was well summarized by another expert who argued "that only rigorous political standards will lead to a wide adoption of alternative fuel-powered HDTs". He added that "financial incentives will then help to spur

the penetration rate of low-emission HDTs in Germany". Government incentives are also reported as a purchasing motivator of low-emission passenger cars (Gallagher and Muehlegger, 2011). The survey results of Sierzchula (2014) show that most firms utilize government grants to compensate for high purchasing prices of low-emission vehicles and utilize them to overcome uncertainties of new technologies.

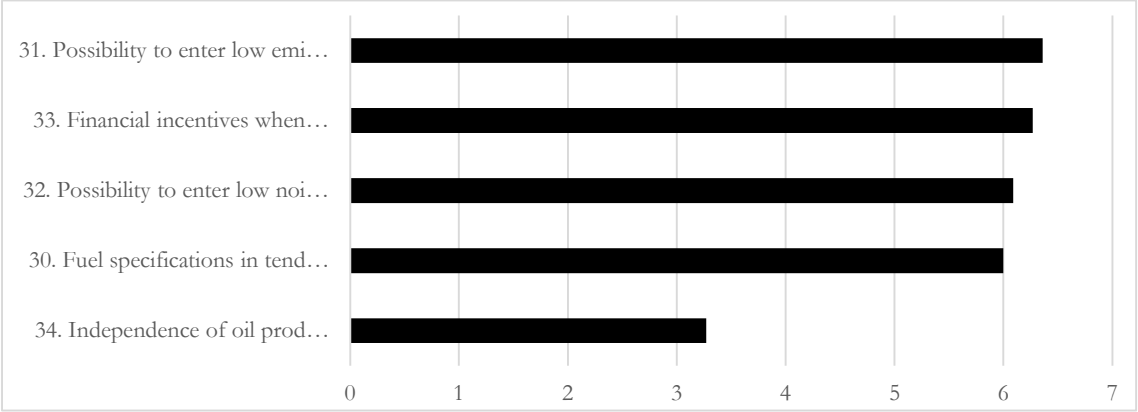

Figure 6: Relative importance of political factors

2.4.3 Part B: Switching from diesel to alternative fuels

The following sections provide an overview of the main motivators, barriers, and ways to overcome the main barriers when switching from diesel-powered HDTs to battery electric (BE), fuel cell electric (FCE), compressed natural gas (CNG) or liquefied natural gas (LNG) HDTs in Germany.

During the face-to-face workshops in January 2018, the experts selected electric as well as natural gas drives as the most promising technologies to reduce emissions from HDTs in Germany. According to the workshop participants, electric vehicles can be divided into BE vehicles where a battery powers the electric motor and hydrogen FCE vehicles where electricity is generated through an electrochemical process to power the electric motor (Mahmoud *et al.*, 2016). On the other hand, natural gas can be used as vehicle fuel in the form of CNG or LNG. While CNG is made by compressing natural gas, LNG is made by cooling natural gas down to -162°C where it reduces its volume around 600 times and becomes liquid (Pfoser, Schauer and Costa, 2018). Following the EIO (2018), BE, FCE, CNG and LNG

HDTs can be defined as eco-innovations as they are significantly improved products compared to conventional diesel-powered HDTs.

Based on the results of the first round, we presented the consolidated lists of 119 motivators, barriers and possible ways to overcome those barriers for each of the four technologies. We asked the participants to select the three most important criteria which will be summarized in Fig. 7 to 10 and discussed in the following sections including expert comments for additional input.

2.4.3.1 Battery electric heavy-duty trucks

Compared to BE passenger cars, BE HDTs remain exotic. Just a few manufacturers exist that offer BE HDTs for the European or German market. While writing, we identified mainly small manufacturers such as Framo (Framo, 2018) and E-Force (E-Force, 2018) that purchase available diesel-powered HDTs from large manufacturers and electrify them. As of February 2019, large European truck manufacturers such as Daimler (Daimler, 2018a), MAN (MAN, 2019a) and DAF (DAF, 2018) have started pilot tests with few selected customers.

Motivators: The possibility to enter low-emissions zones was chosen as the most relevant motivator to adopt BE HDTs. One expert explained that legal restrictions such as diesel bans, and public interest increase the general interest in BE vehicles. The second motivator, TCO benefits, seems to be contradictory, however, findings by Zhou *et al.* (2017) show that there are situations where BE trucks can be used as cost-efficiently as diesel trucks since they benefit from lower fuel costs. Nevertheless, participating experts had contrary viewpoints on that issue as one respondent noted that the purchasing price of BE HDTs and the necessary charging station belong among the top barriers without publicly available charging points. Other experts commented that reduced fuel costs lead to a positive business case considering life cycle costs. Reduced noise and Tank-to-Wheel emissions are general characteristics of electric vehicles and were selected as other main motivators compared to diesel HDTs. An expert highlighted that both aspects should not be underestimated as especially BE HDTs will be used in urban logistics due to the limited driving range.

Barriers: Despite the possibility of a positive overall TCO, experts selected the high purchasing price as the top barrier when switching from diesel to BE HDTs. Davis and Figliozzi (2013) evaluated the competitiveness of electric delivery trucks and concluded that savings from operational costs must be high enough to overcome the initial purchasing price of an electric truck. Furthermore, the authors note that "fuel price, projections about battery costs and lifetimes, and vehicle utilization are the key factors that determine the competitiveness of electric trucks" (Davis and Figliozzi, 2013, p. 22). Several respondents argued that currently available BE HDTs are two to three times more expensive than common diesel HDTs which also results from the fact that small manufacturers buy available diesel-powered trucks that will be electrified. Consequently, experts noted that reliability and residual value of those trucks are currently unknown. We could follow contrary opinions concerning battery costs among the panelists. While two experts explained that high purchasing prices result from expensive battery packs, two others argued that prices are likely to decrease within the next decade. Those panelists also explained that battery capacity will increase what leads to a higher driving range. Nevertheless, the panel listed the currently low driving range as another main barrier when switching from diesel- to BE-powered HDTs. Daimler (2018) as well as MAN (2019) list a maximum driving range of up to 200 km for their BE trucks that are currently being tested. One expert argued that most trucks drive less than 150 km per day and could be powered by batteries to reduce emissions. Third, experts evaluate the lack of charging stations suitable for HDVs as another main barrier. For instance, the battery packs of the "Daimler eActros" have a capacity of 240 kWh compared to 17.6 kWh used in the Smart EQ fortwo passenger vehicle or 37.9 kWh in the BMW i3 (Daimler, 2018b; Smart, 2019; BMW, 2019). Accordingly, BE HDTs need a higher charge rate than electric cars to recharge batteries in a reasonable time.

Solutions: Due to the expensive initial purchasing price of BE HDTs, panelists suggest subsidies and other financial incentives to reduce the burden when switching from diesel- to BE-powered trucks. In June 2018, hence, after the second Delphi round, the German government announced to provide a subsidy of 40,000 Euros per electric truck which are also exempted from German highway toll since January 2019 (BMVI, 2018, 2019c). One expert commented that BE HDTs are still in the early stages and argued that battery technology will further develop what compensates current disadvantages rather soon. Nevertheless, he indicated that

the lack of charging points is currently a knock-out criterion for the comprehensive adoption of BE HDTs in Germany, too. Related to planned CO_2 targets for trucks, the European Automobile Manufacturers Association (ACEA) notes that high-power charging stations of up to 350 kW are being implemented across the EU for passenger vehicles but are not usable for trucks. According to the ACEA, a minimum of 6,000 charging stations with more than 500 kW is necessary across the EU which have not even been developed yet. Above all, a standard plug for BE HDTs is still missing. The ACEA argues that no publicly available charging points existed for trucks with more than 150 kW across Europe in 2018 (ACEA, 2019). Introducing low-noise and low-emission zones was another suggestion to overcome existing barriers what is in line with the diffusion of eco-innovation theory as regulatory push is usually needed for a successful product introduction (Rennings *et al.*, 2006). Participating experts justified this radical step by pushing large European truck manufacturers towards electrification of HDTs as well as increasing spending in battery research and development which leads to decreasing prices and increasing battery capacities.

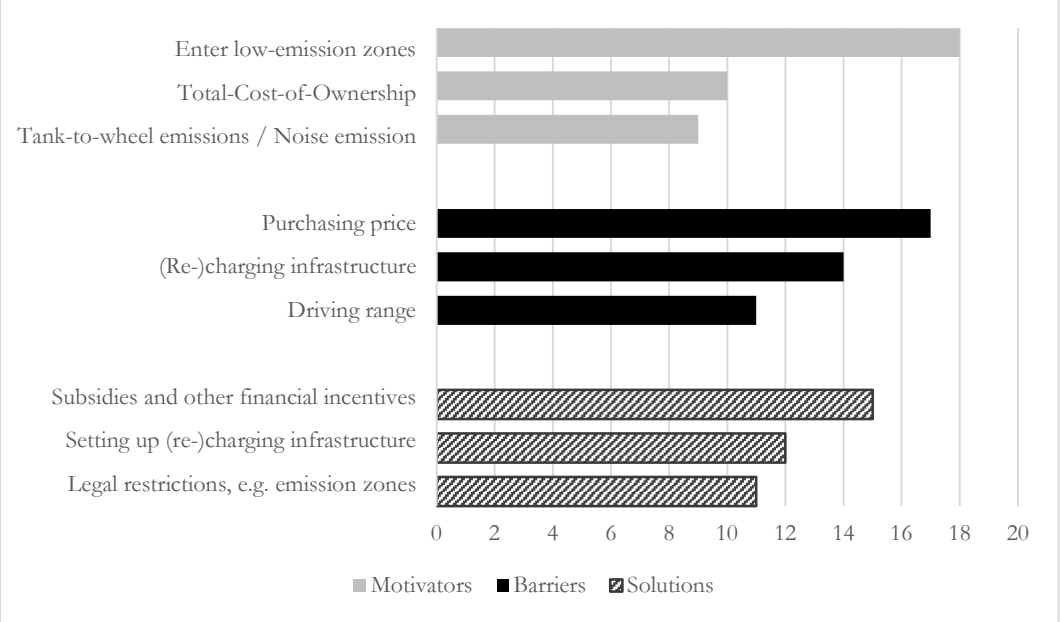

Figure 7: Motivators, barriers, and solutions to switching to BE HDTs

2.4.3.2 Fuel cell electric heavy-duty trucks

Other than BE HDTs, there are no commercially available FCE HDTs available in Germany or Europe yet. However, first prototypes are currently being tested. At the time of writing,

the Swiss company Coop was testing a 34 ton FCE truck (H2Energy, 2017) and a consortium with 15 partners aims to build a 27 ton FCE truck in Europe (WaterstofNet, 2018). In September 2018, the South Korean manufacturer Hyundai presented an FCE HDT that is set to be launched in Europe in 2019 (Hyundai, 2018). Due to the interest from European customers, the American truck company Nikola Motor has created the hydrogen FCE truck Nikola Tre for the European market. First tests in Europe are planned around 2020 in Norway (Nikola Motor, 2018).

Motivators: Similar to BE HDTs, Tank-to-Wheel emissions, and the possibility to enter low-emission zones were evaluated as the main strengths of FCE HDTs. In addition, respondents selected the maximum driving range as the third main motivator of the technology. Kast *et al.* (2017) analyzed FCE medium and heavy-duty trucks (MHDTs) and their results indicate that hydrogen onboard storage can satisfy the vehicle range requirements of more than 90% of daily routes in the United States. The American manufacturer Nikola Motor announced in its press release a maximum driving range of up to 1,200 km for its FCE HDT which will fit within all European length and size restrictions (Nikola Motor, 2018). However, a participant argued that storing hydrogen is complicated and, in contrast to other countries, current European restrictions in length and size do not allow unlimited hydrogen storage onboard. Thus, long-haul operations will be difficult without adjusting such strict European restrictions as well as further technology research and development. According to Hyundai, the maximum driving range of the planned FCE HDT will be around 400 km (Hyundai, 2019a). One expert summarized that the technology "is the best solution for current conflicts regarding CO_2 reduction and other harmful emissions". Another respondent commented that "only FCE trucks ensure zero emission trucking with an acceptable driving range, short refueling time and a reasonable payload capacity".

Barriers: The Delphi panel selected the missing hydrogen fueling infrastructure across Germany as an essential barrier for wide adoption. Comparable to electric charging points, most of the existing 64 hydrogen stations in Germany as of April 2019 are not usable for HDVs due to space restrictions and differing hydrogen pressure (H2 Mobility, 2019). One expert stated that there was no standard defined yet and explained that HDVs will most likely use 350 bar whereas FCE passenger cars are currently constructed for 700 bar of use. This argumentation corresponds to the study of Kast *et al.* (2017) who consider 350 bar for medium

trucks and heavier. Besides, current prototypes require a pressure of 350 bar, for instance, the 34 ton FCE prototype truck tested by Coop in Switzerland as well as the planned FCE HDT from Hyundai (H2Energy, 2017; Hyundai, 2019a). However, the ACEA argues that long-haul trucks require liquefied hydrogen or 700 bar pressure, as planned by Nikola Motor, to realize long distances but those filling stations do not exist yet (Nikola Motor, 2018; ACEA, 2019). The current prototype stadium was selected as another main barrier of the technology. This is supported by a study from Roland Berger Consulting that investigates business cases for FCs and hydrogen applications from August 2017 and classifies the technology readiness level (TRL) of FCE HDTs as 6 (prototype) on a scale from 1 (idea) to 9 (fully commercial) (Roland Berger GmbH, 2017). On the other hand, FCE passenger cars are already available in Germany, for instance, the Toyota Mirai and the Hyundai NEXO. However, FCs to power an electric motor are still expensive what was chosen as another main barrier of FCE HDTs. To our knowledge, there were no official prices for commercially available FCE HDTs announced yet, but current prices of FCE passenger cars serve as an indication for the FC price premium. While writing, the official price of the Hyundai NEXO is 69,000 Euros in Germany whereas prices of a diesel-powered Hyundai Tucson start from 25,520 Euros (Hyundai, 2019b). Thus, one expert summarized that FCE HDTs will not be a viable economic option until 2030 due to the current prototype level and crucial technological challenges. Another expert criticized the current inactivity of European truck manufacturers regarding FCE vehicles and claims for strict legislative changes.

Solutions: Most experts see a price reduction of FCs as an important step towards the future adoption of FCE HDTs in Germany. One expert argued that a clear implementation strategy is missing that would result in lower FC prices as well as in reduced hydrogen storage costs. The same expert also refers to China where the government invests heavily in FCE vehicles. For instance, Ballard Power Systems, a Canadian developer and manufacturer of FCs announced that the Chinese company Shanghai Edrive will assemble Ballard FCs to reach the annual production targets of 3,000 FCE vehicles by 2020 and 30,000 by 2025 (Ballard, 2017). Moreover, China aims to have over 300 hydrogen refueling stations in operation by 2025 and more than 1,000 stations by 2030 as described in the Chinese "Hydrogen Fuel Cell Vehicle Technology Roadmap" (SAE China, 2016). In line with the diffusion of eco-innovation theory, the panel suggested subsidizing European truck manufacturers that invest in the

technology. While truck customers would generally benefit from FCE HDTs, manufacturers bear higher costs than their competitors that invest in FCE trucks at a later stage. The third solution suggested by the panel is to intensify research and development. The German government launched the National Hydrogen and Fuel Cell Technology Innovation Program for research and development funding in the field of hydrogen and FCs (BMVI, 2019b). However, one expert argued that subsidies as well as research and development are important, but secondary without a clear governmental strategy.

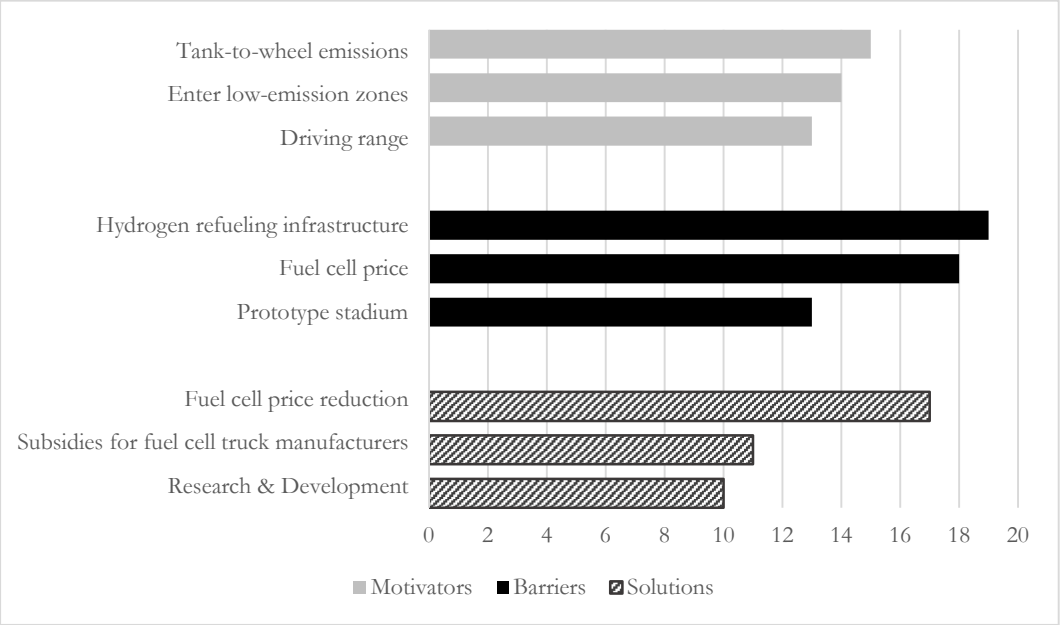

Figure 8: Motivators, barriers, and solutions to switching to FCE HDTs

2.4.3.3 Compressed natural gas heavy-duty trucks

Compressed natural gas (CNG) is a comparably mature technology which is also used in passenger cars, for instance, the Volkswagen Golf TGI (Volkswagen, 2019). CNG HDTs are available from different large European truck manufacturers, e.g. IVECO (IVECO, 2018) and Scania (Scania, 2018).

Motivators: The Delphi panel selected the availability of CNG HDTs from large European truck manufacturers as the top motivator to switch from diesel to this technology. One expert commented that CNG can be evaluated as a reliable technology that could be used immediately in daily logistics operations. Another expert noted that CNG is a viable solution for regional operations of up to 300 km. According to Scania (2017), the maximum range of

CNG HDTs is approximately 500 km. However, an expert argued that CNG HDTs could be substituted by BE trucks soon due to quick technological developments. Furthermore, the panel chose the possibility to enter low-emission zones as another main advantage of the technology. The positive TCO was selected as the third motivator when switching to CNG-powered HDTs in Germany. A study, commissioned by the German government, compared diesel and natural gas HDTs and results show that the premium customers pay for CNG HDTs is paid back in less than four years. However, the authors note that results are use-case dependent and indicate that TCO calculations can change quickly due to various factors that need to be considered carefully (Lischke *et al.*, 2015).

Barriers: Compared to other technologies, experts see comparably little environmental benefits of CNG HDTs. A participating consultant stated that CNG is still a fossil fuel and will not help to reach the CO_2 reduction targets. This corresponds to the results presented by Sen, Ercan and Tatari (2017) who compared diesel and alternative fuel-powered HDTs in the United States and concluded that CNG trucks do not improve life-cycle environmental impacts. The panel evaluated the cheap diesel price as well as the poor CNG fueling infrastructure for HDTs as other main barriers of the technology. Several panelists argued that a satisfactory CNG infrastructure exists, but most stations do not offer necessary capacities for HDTs. According to the European Natural & bio Gas Vehicle Association (NGVA), 854 CNG stations exist in Germany as of April 2019, but most of them are designed for passenger car use only (NGVA, 2019).

Solutions: Among others, experts claim subsidies and other financial incentives to outweigh existing disadvantages of the technology. According to Lischke *et al.* (2015), CNG HDTs are around 20,000 Euros more expensive than their diesel-powered counterparts. In June 2018, the German government announced a purchasing subsidy of 8,000 Euros per CNG truck (BMVI, 2018). Moreover, since January 2019, natural gas trucks are exempted from the German highway toll for an initial period of two years (BMVI, 2019c). Experts also suggest the introduction of legal restrictions to make CNG a more attractive alternative for potential users. In order to reach defined sustainability targets and to improve environmental benefits of CNG, experts assessed the use of biomethane as an important way to enhance its ecological impact. According to Goulding *et al.* (2017), biogas is produced through an anaerobic digestion process and helps to reduce GHG emissions in the transportation sector. The authors describe

that biomethane "is typically injected into the natural gas network where it can be used as a substitute for natural gas in any blend proportion to form bio-CNG" (Goulding *et al.*, 2017, p. 80). However, an expert noted that "the amount of biomethane produced is very limited and either enough to power all city buses in Germany or a significant number of trucks or cars".

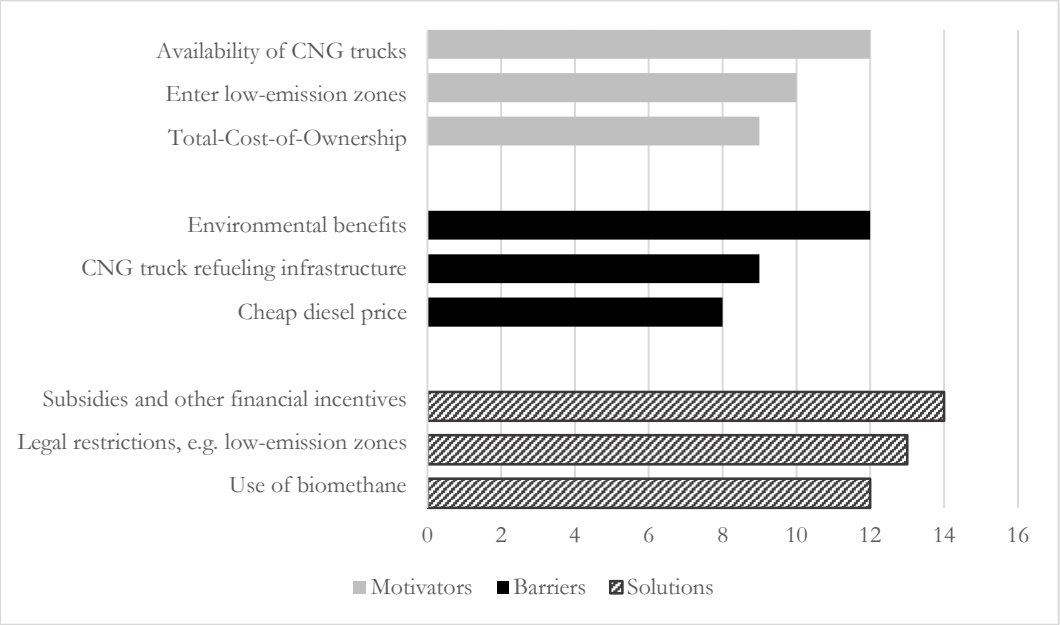

Figure 9: Motivators, barriers, and solutions to switching to CNG HDTs

2.4.3.4 Liquefied natural gas heavy-duty trucks

Liquefied natural gas (LNG) is mainly used for heavy-duty road transport or shipping and is another possibility to reduce GHG emissions from HDTs. LNG trucks are available from various European truck manufacturers such as IVECO (IVECO, 2018), Scania (Scania, 2018), and Volvo (Volvo, 2018a).

Motivators: Fig. 10 illustrates that the high driving range of LNG HDTs was chosen as the main advantage of the technology by the expert panel. For instance, the IVECO Stralis equipped with two LNG tanks ensures a maximum driving range of up to 1,600 km (IVECO, 2019). One Delphi participant commented that LNG is currently the only viable alternative for diesel-powered HDTs and long-haul transports. Furthermore, the panel selected the competitive TCO as another driver when switching from diesel- to LNG-powered HDTs. According to Lischke *et al.* (2015), LNG HDTs in Germany pay back after three to six years

compared to diesel-powered HDTs. However, similar to CNG, the authors note that TCO calculations of LNG HDTs can change quickly due to varying circumstances such as increasing taxes on natural gas (Lischke *et al.*, 2015). Lastly, participants highlighted the possibility to enter low-emission zones as well as the reduced air pollution of LNG powered HDTs as important motivators. Results presented by Osorio-Tejada, Llera-Sastresa and Scarpellini (2017) confirm that the use of LNG decreases GHG emissions by up to 20% and eliminates almost 100% of occurring sulfur oxides. One participant summarized that LNG "is an existing alternative for heavy-duty long-haul transports and is already a fully accepted technology in other European countries, but not yet in Germany".

Barriers: The main barrier of the technology is the almost non-existent LNG fueling infrastructure across Germany which was also criticized by the ACEA (ACEA, 2019). As of April 2019, 195 LNG fueling stations exist across Europe. Only three of them are located in Germany compared to 27 stations in the Netherlands, 43 in Spain and 46 in Italy (NGVA, 2019). According to the ACEA, a minimum number of 1,000 LNG stations is required across Europe (ACEA, 2019). The high purchasing price is another main barrier when switching to LNG HDTs. Lischke *et al.* (2015) describe that the purchasing costs of an LNG HDT are 35,000 Euros to 50,000 Euros higher than those of comparable diesel-powered HDTs. The third barrier is the lack of brand and model variety. One participant indicated that German truck manufacturers do not offer LNG-powered vehicles in Europe. Another expert stated that more truck manufacturers should enter the market what could lead to a price reduction of expensive LNG tanks and ultimately also to an increasing number of LNG fueling stations across Germany. However, another candidate noted that European truck manufacturers seem to show an increasing interest in the technology resulting from the worldwide demand for LNG HDVs.

Solutions: Due to the missing infrastructure, most experts commented that a comprehensive LNG infrastructure across Germany needs to be established. The "Blue Corridor Project" was supported by the EC from 2013 to 2017 to facilitate the adoption of LNG stations across Europe but most stations are currently located in western and southern Europe. An expert explained that LNG terminals are used for the distribution of LNG and are located in western and southern European countries because of their harbors and long coastlines. According to the German Ministry for Economic Affairs and Energy (BMWi), LNG supply can be

theoretically secured through other European countries, but a German consortium is currently planning the first LNG terminal in Brunsbuettel (BMWi, 2019b). Subsidies and financial benefits by the German government were selected as another way to overcome the barriers of LNG HDT adoption in Germany. As previously described, the purchasing price of LNG HDTs is 35,000 Euros to 50,000 Euros higher compared to diesel-powered HDTs (Lischke *et al.*, 2015). Thus, the Ministry of Transport funds the purchase per LNG truck with an amount of 12,000 Euros. In addition, LNG trucks are exempted from German highway tolls from January 2019 to January 2021 (BMVI, 2018, 2019c). The experts recommended legal restrictions such as low-emissions zones as another possibility to spur the penetration rate of LNG HDTs in Germany.

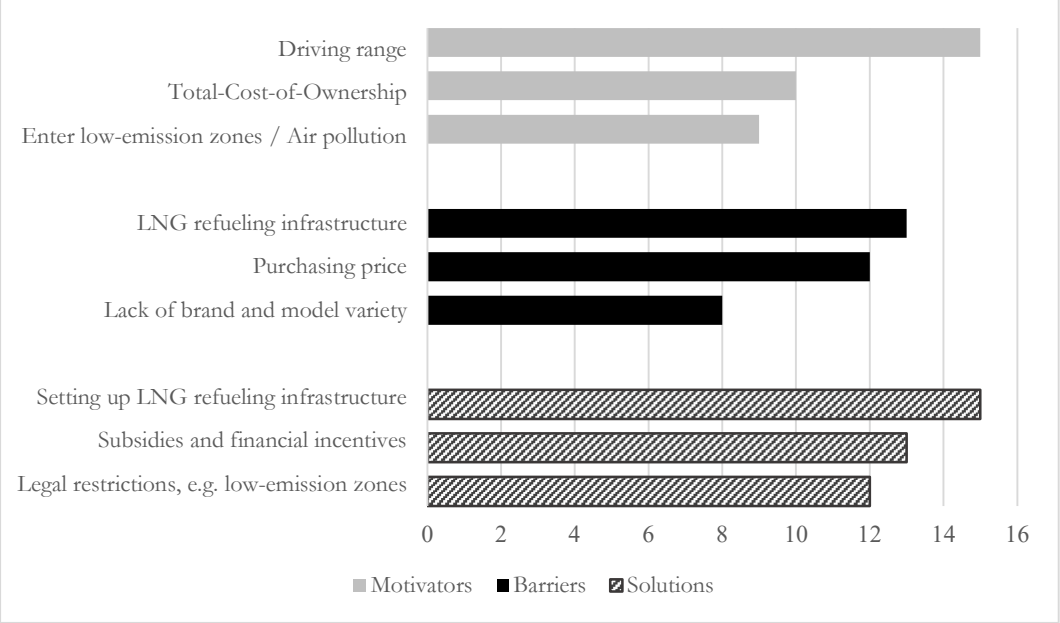

Figure 10: Motivators, barriers, and solutions to switching to LNG HDTs

2.5 Conclusion

Part A of our study aimed to present a comprehensive list and ranking of factors that affect the purchasing decision and operation of alternative fuel-powered HDTs in Germany. Part B aimed to identify specific technologies that have the potential to reduce emissions from diesel-powered HDTs as well as to present the most important motivators, barriers, and possible ways to overcome barriers when switching from diesel to the identified low-emission technologies.

By conducting a Delphi study among a group of experts from different sectors, we found out that a truck's reliability, an available fueling/charging infrastructure, the possibility to enter low-emission zones as well as current and future fuel costs are key factors when purchasing and operating an alternative fuel-powered HDT in Germany. Despite the availability of low-emission technologies which could substitute diesel engines immediately, just a few alternative fuel-powered HDTs are currently registered in Germany. The diffusion of innovations follows a process of uncertainty-reduction where potential users seek information to reduce the uncertainty of a new product (Rogers, 1983). Similar to early research on low-emission passenger cars (e.g. Dyerson and Pilkington, 2005), information gathering about the reliability or operating costs of low-emission HDTs is constrained what leads to low adoption rates among potential users. Pilot tests and first "hands-on" experience can be promising possibilities to reduce skepticism about innovations (Schulte, Hart and Van der Vorst, 2004). As face-to-face communication seems to be more promising than other communication channels, the demonstration of innovative technologies may then help to mobilize innovators and early adopters to switch from diesel to environmental-friendly HDTs (Karakaya, Hidalgo and Nuur, 2014). Following Rennings *et al.* (2006), environmental policy instruments and financial support from innovation policy could additionally reduce existing skepticism of truck manufacturers that are willing to invest, for instance, in FCE HDTs, but also of customers that would like to substitute their diesel-powered truck fleet. We assume that strict legal requirements would lead to an increasing awareness of presented environmental factors which were evaluated by the experts more as a bonus of alternative drives and not as a top priority. However, the expert group also suggested the introduction of legal restrictions to force truck manufacturers to invest in environmental-friendly technologies, but also customers to switch to alternative fuel-powered HDTs. Moreover, subsidies and financial incentives were recommended by the experts, too, and could help to overcome the existing barriers of the four presented technologies. The German government announced subsidies when purchasing natural gas and electric trucks as well as the exemption from German highway tolls for low-emission trucks since January 2019. However, due to the findings of this study, financial incentives are currently less effective as potential customers will not switch to alternative fuel-powered HDTs without a comprehensive charging and fueling infrastructure across Germany. Our results show that an existing infrastructure is one of the most important factors and was

selected as a main barrier when switching from diesel to the four presented low-emission technologies. Consequently, as environmental benefits will mainly occur through customer use, we recommend to setting up a comprehensive charging and fueling infrastructure suitable for HDTs first what will then help to spur the penetration in combination with financial incentives. Nevertheless, to drastically reduce emissions from HDTs, a close collaboration between truck manufacturers, customers, infrastructure experts and governmental institutions is essential.

Our study is not without limitations. As research on BE, FCE, CNG and LNG HDTs is rather limited, an identification of motivators, barriers, and ways to overcome barriers based on an extensive desk research was not feasible in the case of Part B. As a result, we followed the traditional Delphi approach for Part B and generated a list of factors by asking the expert group in open-ended question format for relevant arguments. Due to time constraints, we could not conduct a third Delphi round which would have allowed us to statistically analyze consensus and stability of Part B results. Besides, presented information concerning FCE HDTs such as the maximum driving range is mainly hypothetical as FCE HDTs are not commercially available yet, but first prototypes are currently being tested and FCE HDTs are to be released shortly. The experts evaluated the FC technology as a promising way to reduce emissions from HDTs. The adoption of FCE HDTs together with the optimal location of hydrogen fueling stations are therefore interesting directions for future research. In our study, we have focused on Germany, but our research reveals the possible extension to other countries as the current fueling/charging infrastructure, incentive programs and vehicle regulations differ among various countries. Furthermore, Sen, Ercan and Tatari (2017) demonstrate that life cycle emissions and costs differ greatly even within the same country due to the different ways of electricity generation. A detailed analysis concerning life-cycle costs and well-to-wheel emissions of the four presented technologies could, therefore, be other highly interesting research opportunities.

The second chapter set the stage for the remainder of this dissertation by conducting a Delphi study with several experts from academia and industry in order to analyze the research topic from a broader perspective. The first research question helped us identifying a comprehensive list of 34 factors and how they affect the purchasing decision and operation of alternative fuel-powered HDTs in Germany. The second research question of this chapter supported the

identification of promising alternative fuels and powertrains which could substitute current diesel-powered HDTs. The described motivators and barriers of each technology pave the way for the third chapter of this dissertation project as we are interested in how the different technologies will change over time with respect to costs, technical specifications or self-driving technology and how truck customers value such attributes. Thus, we are conducting a choice-based conjoint experiment with employees from freight companies in the following chapter to better understand how they assess certain characteristics of innovative HDTs and develop different future scenarios to test truck customers' future preference shares.

3. Preferences for autonomous and alternative fuel-powered heavy-duty trucks in Germany

The following chapter is based on Anderhofstadt and Spinler (2020b) 'Preferences for autonomous and alternative fuel-powered heavy-duty trucks in Germany' [2]

3.1 Introduction

Digitization and sustainability are two disruptive megatrends which will transform the transportation and logistics industry over the next years. According to the latest "DHL Logistics Trend Radar", self-driving vehicles and green energy logistics will reshape the industry significantly (DHL, 2018). The Paris Agreement is considered a milestone in global climate policy as it is the first international response to the threat of climate change. The agreement entered into force in November 2016 and aims to keep the global temperature increase well below two degree Celsius above pre-industrial levels (UNFCC, 2019b). The Kyoto Protocol from 1997 specifies the six most important greenhouse gases (GHG): carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride (UNFCC, 2019a). Carbon dioxide (CO_2) is the primary GHG emitted through human activities and is naturally present in the atmosphere as part of the Earth's carbon cycle, however, human activities such as burning fossil fuels have substantially contributed to alter this cycle since the Industrial Revolution (EPA, 2019). In 2017, global CO_2 emissions hit a new record high and amounted to 36,153 million tons. China (9839 million tons) and the United States (5270 million tons) are the top emitters in the world (Global Carbon Atlas, 2020). With a total of 905 million tons, Germany was by far the largest contributor of GHG emissions across the European Union (EU) followed by the United Kingdom (470 million tons) and France (466 million tons) (EEA, 2018). To achieve GHG neutrality by the middle of the century, the German government adopted the "German Climate Action Plan 2050" which specifies emission reduction targets for the different sectors. The energy sector (311 million tons), the industry sector (196 million tons) and the transportation sector (162 million

[2] Anderhofstadt, B. and Spinler, S. (2020b) 'Preferences for autonomous and alternative fuel-powered heavy-duty trucks in Germany', Transportation Research Part D: Transport and Environment, 79, Article 102232.

tons) were the three most emitting sectors in 2018. From 1990 to 2018, GHG emissions from transportation decreased by 0.9% only whereas emissions from energy and industry fell by 33.4% and 30.7% respectively. Around 96% of emissions from transportation result from passenger cars (60.6%) and commercial vehicles (35.6%) (BMU, 2019a). Despite technological improvements which reduced energy consumption per ton-kilometer, overall emissions from commercial vehicles rose by approximately 50% since 1990 as more vehicles are necessary due to rising road freight transportation in Germany (BMU, 2018).

In this study, we are focusing on heavy-duty trucks (HDTs). According to the German Federal Transport Authority (KBA), the heaviest truck types are rigid trucks with a minimum payload capacity of 12 tons as well as HDT lorries. We summarize both categories as HDTs in this study. Based on the latest registration numbers, only 0.07% (246) of HDTs registered in Germany run on alternative fuels while the share of alternative fuel-powered passenger cars is 1.9% (900,954) and increases steadily (KBA, 2019). For instance, new cars registered in Germany which run on alternative drives had a 54.3% growth rate from 2017 to 2018 (BMU, 2019a). Hence, EU-wide emission limits for manufacturers of heavy-duty vehicles (HDVs) will be introduced for the first time between 2021 and 2030 which have to be reached to avoid costly fines (BMU, 2019a).

Apart from reducing emissions, around 1.35 million people die each year in road crashes worldwide mainly due to human error such as speeding, driving under the influence of drugs or distracted driving (WHO, 2018). According to the German Federal Statistical Office (Destatis), 308,721 people got injured in 2018 as a result of road traffic accidents in Germany and 3275 people died what displays an increase of 3.0% compared to 2017 (Destatis, 2019). Drivers of lorries or rigid trucks with a gross vehicle weight of more than 3.5 tons were involved in 15,805 accidents in 2017 (Destatis, 2018). Another challenge in many countries including Germany is the massive truck driver shortage due to the increase in e-commerce and rising trade volumes (Mittal et al., 2018). According to the German Association of Freight Forwarders and Logistics Companies (DSLV), Germany was facing a shortage of 45,000 drivers in 2017 (DSLV, 2017). Industry growth and retirement contribute to the increasing gap since 67,000 truck drivers retire each year in Germany but only 27,000 drivers receive a truck-driving qualification (DSLV, 2018).

A solution to rising emissions, fatalities resulting from road crashes and the massive truck driver shortage are autonomous and alternative fuel-powered HDTs. However, self-driving vehicles are currently an exotic option and sales numbers of low-emission HDTs remain limited. Thus, greater attention must be devoted to truck customers and how they value the attributes of such innovative HDTs. The research questions which guided the execution of this study are therefore:

How do freight companies in Germany assess the main attributes of autonomous and alternative fuel-powered heavy-duty trucks?

What will be customers' future preference shares for autonomous and alternative fuel-powered heavy-duty trucks in Germany?

We employed a choice-based conjoint (CBC) analysis with employees from freight companies based in Germany to answer our research questions. Since the 1970s, conjoint analysis is a well-established multivariate statistical research method to analyze consumer preferences toward the different attributes of a product (or service) (Green and Srinivasan, 1990). CBC experiments are the most frequently used type of conjoint analyses which simulate a realistic buying situation by presenting a series of varying product concepts based on a predefined set of attributes. The respondents are asked to choose the most attractive product (Jervis, Ennis and Drake, 2012).

The remainder of the study is structured as follows: the next section summarizes the fundamental characteristics of theories about the acceptance and use of new technologies such as alternative fuels and self-driving technologies, followed by outlining the methodological process and design of the conducted CBC experiment. Thereafter, we present and discuss the results before concluding the study.

3.2 Acceptance and use of new technologies

A useful management model called the Unified Theory of Acceptance and Use of Technology (UTAUT) was developed by Venkatesh *et al.* (2003) which helps decision-makers to understand the drivers of adoption and to evaluate the likelihood of adopting an innovation. The developed model is based on other well-known theories such as the Technology

Acceptance Model (TAM) by Davis (1989) or the Theory of Planned Behavior (TPB) by Ajzen (1991). According to Rahman *et al.* (2017) UTAUT, TAM and TPB are the three most frequently used theories to study the acceptance towards new technologies and served as guiding theories in previous research studying alternative fuels and self-driving technology.

TPB is a conceptual framework which is widely used in academia to discuss complex human social behavior. Ajzen (1991) states that (i) attitude toward a behavior, (ii) subjective norms as well as (iii) perceived behavioral control can accurately predict behavioral human intentions. The first predictor, attitude toward a behavior, describes the degree to which an individual evaluates the behavior in question as beneficial or not such as buying a low-emission vehicle instead of a conventional one. Subjective norms refer to the social pressure of a person's network toward the behavior which could be pressure from policy, customers or society to adopt eco-innovations. The third determinant is perceived behavioral control and displays a person's belief how difficult it is to perform the behavior and also considers past experiences (Ajzen, 1991). For instance, it might be difficult to pursue a fleet manager to buy an electric truck if he felt dissatisfaction with an electric passenger car before. TPB was therefore successfully used in previous studies focusing on environmental responsibility and the adoption of innovations. For instance, Kaplan *et al.* (2016) proposed a framework based on the TPB which provides barriers and drivers to the diffusion of electric vehicles in the commercial sector. The results reveal that it is necessary to explore the linkage between possible cognitive and emotional barriers as well as policies, emotional and cognitive drivers, alongside analyzing the influence of policies and market shares (Kaplan *et al.*, 2016). Interestingly, Gkartzonikas and Gkritza (2019) conducted a review of studies on fully autonomous vehicles and argue that theories such as TPB have not been estimated yet. The authors identified nine relevant factors which influence behavioral intention to use self-driving vehicles: (a) the level of awareness, (b) consumer innovativeness, (c) safety, (d) trust of strangers, (e) environmental concerns, (f) relative advantage, compatibility, and complexity, (g) driver-related seeking scale, (h) self-efficacy, and (i) subjective norms. The latter, subjective norms, is also strongly related to a study conducted by Talebian and Mishra (2018) who predict the adoption of connected autonomous vehicles in their research and note that it is difficult to rely on past experiences in case of radical innovations due to a lack of information. Hence, individuals have to rely on their social network but can be also subject to mass media

communication. The authors state that the attitude toward connected autonomous vehicles is therefore dynamic and varies over time as potential adopters communicate with both satisfied and dissatisfied customers. Another study conducted by Buckley, Kaye and Pradhan (2018) utilized TPB and TAM to analyze drivers' intention to use automated passenger cars and found out that the three predictors of TPB were significant when adopting automated vehicles. TAM is an information technology theory developed by Davis (1989) and focuses on two specific variables that are essential for individuals to reject or accept new technologies: perceived usefulness and perceived ease of use. The latter variable is defined as "the degree to which a person believes that using a particular system would be free of effort" (Davis, 1989, p. 320) whereas the former one is characterized as "the degree to which a person believes that using a particular system would enhance his or her job" (Davis, 1989, p. 320). TAM has been applied to various users and different types of technology (Venkatesh *et al.*, 2003). For instance, the study of Koul and Eydgahi (2018) investigated the adoption of self-driving cars and was guided by TAM. The authors state significant, positive relationships between perceived ease of use of self-driving technology, perceived usefulness of the technology and intentions to adopt self-driving cars. Moreover, the authors found significant, negative relationships between the intention to use a self-driving car, the candidate's age and the years of driving experience. TAM is also one of eight theories that serve as a basis for the coherent UTAUT model, developed by Venkatesh *et al.* (2003). Kaur and Rampersad (2018) state TAM and UTAUT as important adoption models for new technologies as both theories include the following relevant variables: reliability, performance, expectancy, trust, security, and privacy. According to the authors, especially trust, security, and privacy seem to be relevant factors in the autonomous vehicle literature, however, Anderhofstadt and Spinler (2019) found out that also reliability is among the most important factors when operating alternative fuel-powered HDTs in Germany. According to Venkatesh *et al.* (2003), UTAUT outperformed any of the previous technology acceptance models by accounting for 70% of the variance. The authors argue that performance expectancy, effort expectancy, social influence and facilitating conditions are the four main constructs for user behavior and user acceptance. Madigan *et al.* (2017) report that the model has traditionally been utilized to discuss intentions to use information systems, however, recent research indicates that UTAUT can be applied to understand driver acceptance toward new vehicle technologies, too. An adapted version of

UTAUT was integrated by Madigan *et al.* (2017) to study factors which influence the approval of automated road transport systems. It appears that the users' enjoyment, the system's performance, necessary resources to support its use as well as social popularity are relevant factors to use automated road transport systems. Moreover, Sovacool (2017) developed a framework which includes, among others, UTAUT to study the adoption of electric vehicles.

3.3 Research methodology

3.3.1 Choice-based conjoint analysis

Since the 1970s, conjoint analysis is a well-established multivariate statistical research method to analyze consumer preferences toward the different attributes of a product (or service) (Green and Srinivasan, 1990). Although the method is nowadays often used by marketers, discrete choice experiments and conjoint analysis are originally based on the work of Luce and Tukey (1964), a statistician and a mathematical psychologist. The first consumer-oriented conjoint article was published by Green and Rao (1971) (Green and Srinivasan, 1978).

Nowadays, the most frequently used type of conjoint analysis is the choice-based conjoint (CBC) analysis which became popular in the 1990s (Orme, 2009; Jervis, Ennis and Drake, 2012). CBC experiments simulate a realistic buying situation by presenting a series of varying product concepts that are based on a predefined set of attributes. Thus, participants are confronted with a trade-off situation since they have to choose the most attractive product concept (Jervis, Ennis and Drake, 2012). CBC frameworks follow the random utility theory as customers usually choose the product that maximizes their personal utility by evaluating the different attributes of a product (Lancaster, 1966; McFadden, 1986). We chose CBC analysis as the method of choice because it is considered to be a more realistic approach since respondents choose one full product concept which consists of all defined attributes what leads in return to more reliable results than ranking or rating individual attributes (Shamir and Shamir, 1995). In addition, both existing and hypothetical products can be tested in CBC experiments making it a suitable research method to analyze autonomous and alternative fuel-powered HDTs (Scherer, Emberger-Klein and Menrad, 2018). In CBC experiments, it is also possible to include a dual-response option in which respondents decide in an additional question whether they would really buy the chosen product or not what leads to a more

realistic approach rather than simply rejecting all presented product concepts (Hille, Weber and Brosch, 2019). Finally, Hierarchical Bayes (HB) estimation can be applied nowadays due to fast computers which clearly improves the results of traditional estimation methods such as logit or ordinary least square regression (Orme, 2000). Compared to other models, HB estimation allows researchers to calculate part-worth utilities at the individual level (Apostolakis *et al.*, 2018). Nonetheless, some aspects of CBC experiments need to be addressed carefully. For instance, one choice set usually includes three to four product concepts which consist of the different attributes. Hence, a carefully designed experiment is essential to avoid research fatigue and ultimately resorting to problematic simplification strategies as respondents need to process a lot of data before answering a single choice set (Orme, 2009; Sawtooth, 2017). Moreover, it is usually not possible to cover all factors which affect the process of adopting a product in the real world (Hille, Weber and Brosch, 2019). Concluding if particular characteristics of the presented product catch the attention of survey participants is often seen as another disadvantage of conjoint analysis as respondents are unable to articulate attitudes toward new categories (Meyerding and Merz, 2018). Defining the most critical product attributes and levels a priori is therefore essential but is another key challenge when conducting reliable conjoint experiments (Lohrke, Holloway and Woolley, 2010). Lastly, poorly designed studies can lead to the over- or undervaluation of product variables what underlines the importance of carefully designed experiments and pretests (Hackbarth and Madlener, 2013).

Conjoint analysis has already been used in previous studies analyzing consumer preferences toward alternative fuel-powered vehicles. For instance, Lebeau *et al.* (2012) applied a CBC analysis to assess plug-in hybrid and battery electric passenger vehicles. A CBC model was also developed by Eggers and Eggers (2011) to analyze all-electric, range-extend electric, and hybrid cars. Apart from low-emission passenger vehicles, the method has been used in several other studies investigating eco-friendly products, e.g. to assess consumer preferences for bio-based plastic sports equipment (Scherer, Emberger-Klein and Menrad, 2018) or to explore the relative importance of eco-labels for washing machines (Sammer and Wüstenhagen, 2006). Fig. 11 illustrates the different phases of our CBC experiment which will be further described in the following sections.

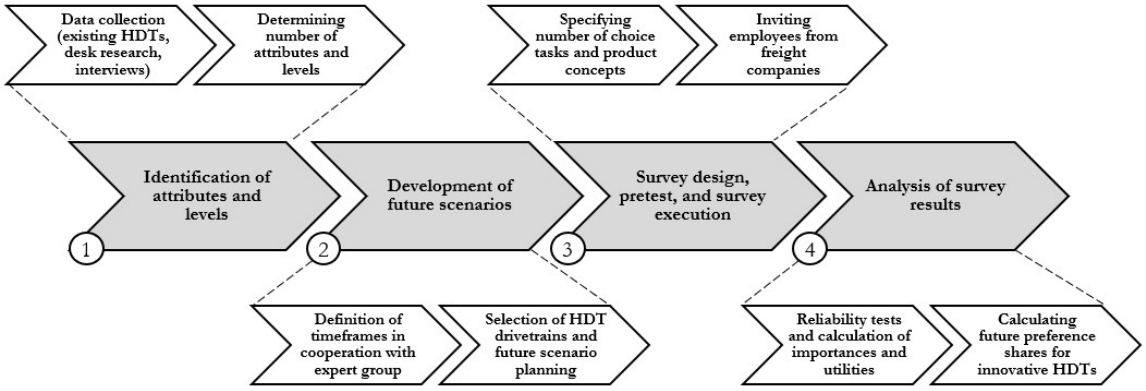

Figure 11: Choice-based conjoint experiment process phases

3.3.2 Identification of attributes and levels

The careful selection of relevant attributes and levels is essential when conducting a CBC experiment. It is recommended to restrict the number of attributes and levels which makes it easier for the participants to evaluate the different product concepts (Rokka and Uusitalo, 2008). An effective CBC design should therefore not include more than six to eight attributes as a higher number may irritate the participants and could lead to superficial replies (Green and Srinivasan, 1990; Hair *et al.*, 2014; Sawtooth, 2019b). The levels of an attribute are used to express the different characteristics of it and according to Orme (2002), fewer than five levels per attribute are suggested which was also applied by other authors (e.g. Sammer and Wüstenhagen, 2006; Lebeau, Macharis and Van Mierlo, 2016; Scherer, Emberger-Klein and Menrad, 2018). We followed previous conjoint studies and derived a list of meaningful attributes and levels based on data from existing alternative fuel-powered trucks, desk research, and semi-structured expert interviews (e.g. Sammer and Wüstenhagen, 2006; Kaufmann, Künzel and Loock, 2013; Scherer, Emberger-Klein and Menrad, 2018). Moreover, our pre-selection was finalized in cooperation with an expert group who further supported the development of future scenarios and will be introduced in the following section. The participants of the final CBC study were instructed to choose the preferred product concept as they were in a real purchase decision and to neglect all other aspects that may affect their choice such as the vehicle design or regulatory barriers.

The first attribute, *driving automation*, refers to automated driving systems which perform certain aspects of the driving task. In its technical standards, the Society of Automotive

Engineers (SAE) defines six levels of driving automation ranging from level 0 to level 5 (SAE, 2019). As a result of the expert feedback and to keep the number of attributes low as well as easily understandable, we included three levels which best reflect the evolution of self-driving trucks. The first level refers to the current status in which all aspects of the driving task are performed by a human driver who can be supported by driving features such as adaptive cruise control (SAE level 0-2). Second, automated driving systems can drive the vehicle under limited conditions, e.g. over long distances on highways (SAE level 3-4). Finally, no human driver is needed as the system is able to perform all driving tasks under all conditions and street types (SAE level 5). The second attribute, *maximum driving range*, is considered an important factor in previous research when it comes to alternative fuel-powered vehicles (e.g. Eggers and Eggers, 2011; Hackbarth and Madlener, 2013; Lebeau, Macharis and Van Mierlo, 2016). Leading German truck manufacturers such as Daimler (2018) and MAN (2019) state a driving range of up to 200 km for their battery electric (BE) trucks. HDTs powered by compressed natural gas (CNG) can drive up to 500 km and vehicles running on liquefied natural gas (LNG) up to 1600 km (Scania, 2017; IVECO, 2019). Fuel cell electric (FCE) HDTs are currently under development but manufacturers promise a maximum driving range between 400 km and 1200 km for trucks which fit within European restrictions (Nikola Motor, 2018; Hyundai, 2019a). The third attribute, *refueling/recharging time*, describes the time to refuel or recharge an empty tank or battery. While the refueling time of natural gas HDTs is comparable to diesel-powered HDTs, the recharging time of BE trucks heavily depends on the truck's battery capacity, the available charging station and the maximum charge rate. The attribute levels are therefore ranging from 10 minutes to 4 hours and 30 minutes. The fourth attribute, *lifetime operating costs*, displays all operational costs of trucking (e.g. fuel costs, taxes, repair and maintenance, etc.) relative to currently available state-of-the-art diesel-powered HDTs. The four attribute levels were defined as percentages ranging from -40% to +20% as it is difficult to generalize the operational costs in Euros, for instance, due to highway tolls paid per kilometer driven. The *purchase price* relative to a currently used state-of-the-art diesel-powered HDT was specified as the fifth attribute. The provided attribute levels were also listed as percentages ranging from -20% to +40% as purchase prices in Euros vary greatly, for instance, due to the vehicle's brand or the level of extra equipment. We are aware that the presented range of -20% to +40% is currently unrealistic for most alternative fuel-powered and

autonomous HDTs, however, we followed Hackbarth and Madlener (2013) and try to avoid a dominance of purchase price over other product attributes. However, financial subsidies for electric and natural gas HDTs are available in Germany and the experts assume that purchase prices are likely to decrease over the next years (BMVI, 2018). The last attribute, *tank-to-wheel (TtW) emissions*, describes on-road emissions relative to currently used state-of-the-art diesel-powered HDTs with attribute levels ranging from -25% for HDTs running on fossil fuels up to -100% for fully electric vehicles. The attributes, definitions and levels are summarized in Table 4.

Table 4: Attributes, definitions, and levels used in the experiment

Attribute	**Definition**	**Levels**
Driving automation	Automated driving systems perform all aspects of the driving task i) under all conditions (SAE level 5), ii) under limited conditions only (SAE level 3-4) or iii) are not available and a human driver performs all aspects of the driving task (SAE level 0-2).	Level 5 Level 3-4 Level 0-2
Maximum driving range	Maximum driving range in kilometers with a full tank or full battery.	1600 km 800 km 400 km 200 km
Refueling/recharging time	Time to refuel the tank or to recharge the battery.	10 min 30 min 1 h 30 min 4 h 30 min
Lifetime operating costs	Lifetime operating costs (fuel, driver, tolls, taxes, insurance, repair and maintenance etc.) relative to a state-of-the-art diesel-powered HDT.	-40 % -20 % 0 % +20 %
Purchase price	Purchase price relative to a state-of-the-art diesel-powered HDT.	-20 % 0 % +20 % +40 %
Tank-to-wheel (TtW) emissions	Tank-to-wheel greenhouse gas emissions, air pollutants and noise emission relative to a state-of-the-art diesel-powered HDT.	-100 % -50 % -25 %

3.3.3 Development of future scenarios

Based on the results of the CBC survey, we aim to display the future shares of preference of truck customers for newly registered autonomous and alternative fuel-powered HDTs in Germany. For the development of scenarios, we conducted semi-structured expert interviews to display the future of HDTs in Germany with reference to the six identified attributes. Five experts from a German multinational automobile manufacturer supported the scenario development process. Three experts work on the company's "Green Logistics Strategy" aiming for a GHG neutral supply chain and have already successfully implemented battery electric (BE) and natural gas HDTs in the company's transportation processes. Furthermore, they are involved in different research projects focusing on sustainable supply chains including alternative fuels. In addition, we interviewed an autonomous driving engineer as well as an expert from the logistics innovation department who is responsible for implementing sustainable and autonomous transport systems including HDVs. In cooperation with the experts, we specified four promising alternative drivetrains which could substitute currently used diesel-powered HDTs and developed a realistic baseline scenario, an optimistic scenario and a pessimistic scenario from 2020 to 2035.

3.3.4 Survey design and pretest

The conducted CBC online experiment was designed with Sawtooth[3] Lighthouse Studio 9.6.1 which is a standard software in academia for creating and analyzing conjoint experiments. It is a widely used software which has been used in several previous conjoint studies (e.g. Lebeau *et al.*, 2012; Loock, 2012; Kaufmann, Künzel and Loock, 2013; Apostolakis *et al.*, 2018; Scherer, Emberger-Klein and Menrad, 2018; Stöckigt, Schiebener and Brand, 2018).

The welcome page of our survey briefly explained the scope of research and methodology used. Thereafter, we surveyed the participants on their freight company to find out more about the number of employees or trucks in operation. We provided a list of definitions for

[3] Additional information can be found under https://www.sawtoothsoftware.com/

each attribute on the following page of the online survey to ensure a common understanding among the participants (see Table 4).

Selecting an appropriate number of choice tasks in CBC experiments is a relevant decision which was studied by Johnson and Orme (1996). The authors re-analyzed 21 CBC data sets and showed that respondents could answer up to 20 choice tasks without degradation in data quality. Nowadays, about ten tasks are recommended as recent research indicates that more questions per participant usually do not reveal additional information and that especially online participants are less patient with long-lasting experiments (Sawtooth, 2019b). Thus, we presented ten random choice tasks and two fixed tasks to each respondent which can be considered as a reasonable number to avoid research fatigue or resorting to simplification strategies. Two fixed holdout tasks were used to measure the reliability of our model and included previously selected attribute levels (Apostolakis *et al.*, 2018). One choice task displayed three product concepts which were presented in full profile designs, i.e. each product alternative consisted of all identified attributes. According to Hair *et al.* (2014), an appropriate conjoint study needs to ensure both a balanced design and orthogonality. We followed Apostolakis *et al.* (2018) and generated a balanced design of presented choice tasks by applying the balanced overlap function provided by Sawtooth software. The balanced overlap design allows a modest amount of level overlap to generate choice tasks in which, for instance, two product concepts show the same attribute level. Some degree of overlap is even recommended to better measure interactions between attributes and to get deeper information about the respondents' preferences (Sawtooth, 2019a). Furthermore, we followed Hille, Weber and Brosch (2019) as well as Scherer, Emberger-Klein and Menrad (2018) and included a dual-response option to each choice task in which respondents decide in an additional question whether they would really buy the chosen HDT or a conventional diesel-powered vehicle. Finally, a pre-study with nine candidates was conducted to test the design of our experiment. After completion, the pretest candidate's feedback indicated that text-only makes it difficult to process all data. Hence, we followed Stöckigt, Schiebener and Brand (2018) and provided text supported by graphics in the final experiment to present the different attribute levels in a visual way which makes it easier for the participants to compare the presented product alternatives. A sample choice task of the final CBC experiment is presented in Fig. 12.

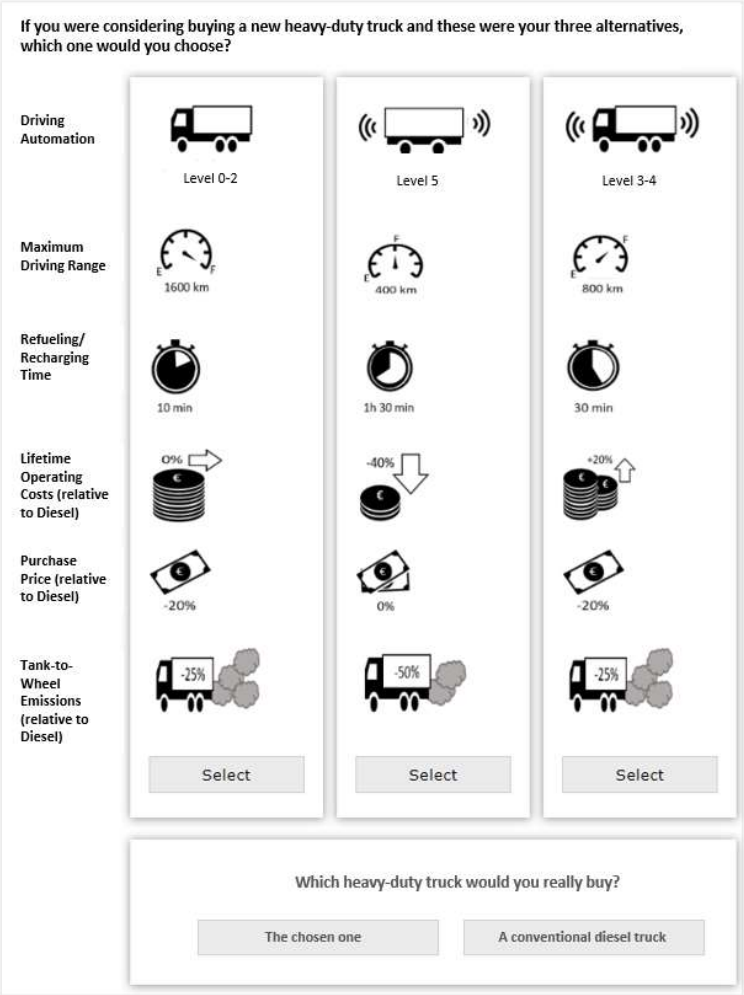

Figure 12: Sample choice task

3.3.5 Sample

End of May 2019, we sent a personal invitation email with the link to our online experiment to 326 employees from freight companies based in Germany. In addition, the link was shared in two logistics online forums and by two DSLV state members (Berlin/Brandenburg and Hesse/Rhineland-Palatinate) as part of their monthly newsletter. According to Hair *et al.* (2014), a minimum of 50 respondents is recommended while Kaufmann, Künzel and Loock (2013) refer in their study to a minimum number of 30 participants for conjoint analysis. For instance, Loock (2012) conducted a CBC experiment with 38 respondents and Lebeau, Macharis and Van Mierlo (2016) with 45 participants to investigate the choice of light commercial battery electric vehicles in city logistics. Mid-July 2019, our online experiment was

opened 185 times, however, the final sample was reduced to 69 as responses were excluded from our analysis if the survey was not completed or if freight companies do not operate any own trucks. Table 5 gives an overview of the final sample. According to the definition of the European Commission (EC), our sample primarily composes of respondents employed at medium firms with 50-249 employees (37.7%) and large firms with more than 250 employees (57.9%) (EC, 2019c). Most freight companies (59.4%) operate more than 100 trucks which are mainly used for long-haul operations (60.9%). 58.0% of our respondents had previous experience with alternative fuel-powered HDTs but only 5.8% with autonomous trucks.

Table 5: Sample

	Frequency (%)	**Respondents**
Number of employees		
1-49	4.4 %	3
50-249	37.7 %	26
250-999	21.7 %	15
1,000-9,999	26.1 %	18
>10,000	10.1 %	7
HDTs in operation		
1-9	2.9 %	2
10-49	23.2 %	16
50-99	14.5 %	10
100-499	34.8 %	24
>500	24.6 %	17
HDTs main field of operation		
Short-haul transportation (<100 km)	33.3 %	23
Long-haul transportation (>100 km)	60.9 %	42
Equal	5.8 %	4
Previous experience with alternative fuel-powered HDTs	58.0 %	40
Yes	42.0 %	29
No		
Previous experience with autonomous HDTs		
Yes	5.8 %	4
No	94.2 %	65

3.4 Results

3.4.1 Data analysis

The average time needed to complete our survey was 9.76 minutes. Of all respondents, 2.9% chose the conventional diesel truck in the provided dual-response option for all twelve choice

tasks, i.e. none of the presented innovative HDTs would be preferred to a conventional diesel-powered HDT. To test the reliability of our model, we followed Apostolakis *et al.* (2018) and designed two identical holdout tasks with manually selected attribute levels which were excluded from the estimation of utilities. Both holdout tasks consist of one rather preferable and two less preferable product concepts and were used to test if participants select product concepts randomly. Moreover, the right position of holdout tasks is crucial as previous research shows that the first tasks of CBC experiments show the biggest noise (Orme, 2014). We therefore placed our holdout tasks at the fifth and twelfth position of our survey. Finally, we calculated the test-retest rate which indicates how often the respondents answered both holdout tasks identically (Apostolakis *et al.*, 2018). The calculated test-retest rate is 91.3%, implying a high internal consistency. In addition, we followed previous conjoint studies and computed the goodness of fit of our Hierarchical Bayes (HB) model displayed by the root likelihood value (RLH) (e.g. Apostolakis *et al.*, 2018; Scherer, Emberger-Klein and Menrad, 2018; Hille, Weber and Brosch, 2019). The RLH value is "the geometric mean of the predicted probabilities and is calculated by taking the nth root of the likelihood where n is the total number of choices made by all respondents in all tasks" (Tabi and Wuestenhagen, 2017, p. 767). Respondents who are selecting product concepts rather randomly show a low RLH score while the best possible theoretical score is 1.0 which correlates to a perfect estimation model. The expected and therefore worst RLH score is 1/k where k is the number of product concepts shown in one choice task (Tabi and Wuestenhagen, 2017). Our HB calculations yielded an average RLH value of 0.637 what is clearly a larger fit than 0.333 what displays a chance model with three product alternatives.

Methods for analyzing CBC data were already available in the 70s and 80s, however, there were no opportunities to calculate part-worth utilities on an individual level until the 90s. Since then, HB models are the preferred method of choice to calculate individual part-worth utilities (Sawtooth, 2009). Part-worth utilities display how strong each attribute level influences the choice of a respondent and can be used to predict how consumers will choose among different product concepts (Green, Krieger and Wind, 2001). Compared to other methods, HB models provide individual part-worth estimates given only some choices per respondent "by "borrowing" information from population information (means and covariances) describing the preferences of other respondents in the same dataset" (Sawtooth, 2009, p. 1).

3.4.2 Importances and part-worth utilities

Based on the calculated HB model, the relative average importance of the six identified attributes is shown in Fig. 13. The importances of the attributes sum up to 100% and were computed by dividing the range of the lowest and highest utility score of an attribute by the sum of ranges across all attributes (Tabi and Wuestenhagen, 2017). Fig. 14, on the other hand, presents the average part-worth utilities which display the relative influence of each attribute level on respondents' choices. Negative utility values such as -1.12 for driving automation level 0-2 are not necessarily unattractive as presented utilities for each attribute are scaled to sum to zero (Orme, 2010).

The results of our experiment indicate that the maximum driving range is the most important attribute. The relevance of an attractive driving range was also discussed in previous research on alternative fuel vehicles (e.g. Hidrue *et al.*, 2011; Lebeau *et al.*, 2012; Ziegler, 2012; Hackbarth and Madlener, 2013; Lebeau, Macharis and Van Mierlo, 2016). For instance, Pfoser, Schauer and Costa (2018) investigated the acceptance of LNG for HDVs and state that alternative technologies such as BE drivetrains have substantial drawbacks as they are characterized by a limited driving range. Hoen and Koetse (2014) conducted a choice experiment to find out more about alternative fuel vehicle preferences for private owners in the Netherlands and describe that negative preferences for electric vehicles are large, especially due to long recharging times and short driving ranges. In addition, the authors report that preferences for electric cars decrease drastically when annual mileage rises. Statistics from the German Federal Transport Authority (KBA) reveal that truck lorries drove on average 96,915 km in 2017 compared to 13,922 km in case of passenger cars (KBA, 2018b). Based on 250 workdays per year, the average daily mileage of a truck lorry is therefore 388 km what is almost seven times as much as the mileage of passenger cars. Anderhofstadt and Spinler (2019) analyzed factors which drive the adoption of low-emission HDTs in Germany and show that the driving range is considered a main motivator when switching from diesel to FCE or LNG HDTs, but a top barrier in case of BE HDTs. The presented average part-worth utilities in Fig. 14 show that 1600 km (1.92) and 800 km (1.53) are strongly preferred to 400 km (-0.36) and especially to 200 km (-3.09). Thus, we assume that the preference for long distances is closely linked to the presented annual mileage driven by HDTs. Moreover, the participants of our survey indicated that their HDTs are mainly used for long-haul operations. The

refueling/recharging time is the second most important attribute which was also considered as a main factor in other studies (e.g. Hidrue *et al.*, 2011; Lebeau *et al.*, 2012; Hackbarth and Madlener, 2013). A conjoint analysis conducted by Lebeau, Macharis and Van Mierlo (2016) explored the choice of battery electric vehicles in urban logistics. The authors found out that a recharging time of 30 min at the depot of a freight company is comparable to a conventional 5 min refueling time since city logistics companies could charge their vehicles at the depot while loading or unloading it. However, as HDTs are usually used for long-haul transportation, refueling or recharging at the depot is not always possible. The calculated average part-worth utilities show that short refueling/recharging times of 10 min (1.66) or 30 min (1.06) are favored over 1 h 30 min (0.12) and 4 h 30 min (-2.84) by our respondents. While natural gas and hydrogen vehicles benefit from short refueling times comparable to diesel-powered HDTs, recharging times of BE HDTs depend on the vehicle's battery capacity and the maximum charge rate at the charging station. For instance, the BE Daimler eActros truck has a battery capacity of 240 kWh compared to 22 kWh in the standard version of the Renault ZOE passenger car (Daimler, 2019b; Renault, 2019). In order to fulfill future CO_2 targets for trucks, the European Automobile Manufacturers Association (ACEA) argues that at least 6000 high-power charging stations with a charge rate of more than 500 kW are needed across the EU to ensure fast-charging possibilities for HDVs (ACEA, 2019). The lifetime operating costs of an HDT were ranked as the third most important attribute followed by the purchase price of the vehicle. Our results are therefore in line with findings from Sierzchula (2014) who studied factors which influence fleet managers to adopt electric vehicles. The author argues that firms, compared to private customers, are more likely to purchase pricier vehicles which benefit from lower operating costs in the long run. It is also important to note that the decision of fleet managers is more complex compared to private households as it involves much larger investments, various vehicles and different driving patterns (Kaplan *et al.*, 2016). Anderhofstadt and Spinler (2019) also showed that current and future fuel costs are more important than the purchase price of low-emission HDTs as fuel costs account for the largest share of annual truck expenses. In accordance with economic theory, lower operating costs and lower purchase prices increase the attractiveness of a vehicle. Hence, lifetime operating costs of -40% (1.59) or -20% (0.93) as well as purchase prices of -20% (1.27) or 0% (1.05) relative to state-of-the-art diesel HDTs are clearly preferred. According to our participants,

driving automation is the fifth most important attribute followed by tank-to-wheel emissions which was rated as the least important attribute. Driving automation level 5 (0.56) and level 3-4 (0.56) are preferred to level 0-2 (-1.12), however, results show that average utilities of level 5 and level 3-4 are identical. Hence, our participants value the benefits of self-driving technology but are indifferent between conditional and full automation. Simpson *et al.* (2019) analyzed the future adoption rate of autonomous trucks and demonstrate several benefits of self-driving technology, e.g. the reduction of accidents, safer working conditions, rising reliability as well as decreasing costs. Another study conducted by Milakis, Van Arem and Van Wee (2017) investigated policy and society related implications of automated vehicles such as travel cost, vehicle ownership, emissions or traffic safety. The authors conclude that the use of automated vehicles can lead to better fuel economy and decreasing emissions. Moreover, automated driving level 3 or higher as well as driver assistance systems are expected to enhance traffic safety but could be ultimately limited due to the coexistence of manually driving humans. Despite numerous advantages of self-driving vehicles, previous studies show that people are also concerned about software hacking or legal issues when using self-driving vehicles (e.g. Kyriakidis, Happee and De Winter, 2015; König and Neumayr, 2017; Gkartzonikas and Gkritza, 2019). Alternative fuel-powered HDTs which reduce TtW emissions by 100% (0.49) are favored over drivetrains which reduce emissions by 50% (0.11) or 25% (-0.61). Interestingly, previous studies do also confirm that other factors such as costs are usually evaluated as more important than environmental aspects. For instance, Knez, Jereb and Obrecht (2014) studied factors that influence the purchasing decision of alternative fuel-powered vehicles and found out that lower emissions are often seen as a bonus but not a top concern. Moreover, previous research emphasizes on the importance of well-to-wheel (WtW) emissions that combine both well-to-tank (WtT) and tank-to-wheel (TtW) emissions (e.g. Ziegler, 2012; Anderhofstadt and Spinler, 2019). However, Alamia *et al.* (2016) note that no WtW emissions standard was defined yet.

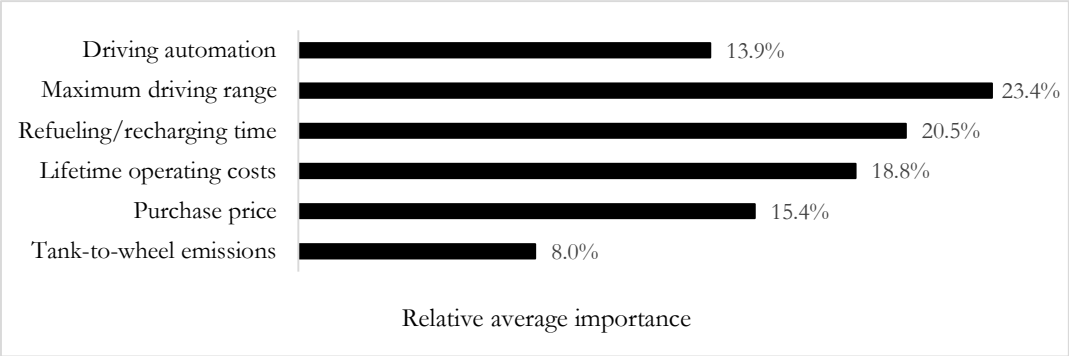

Figure 13: Relative average importance of the presented attributes

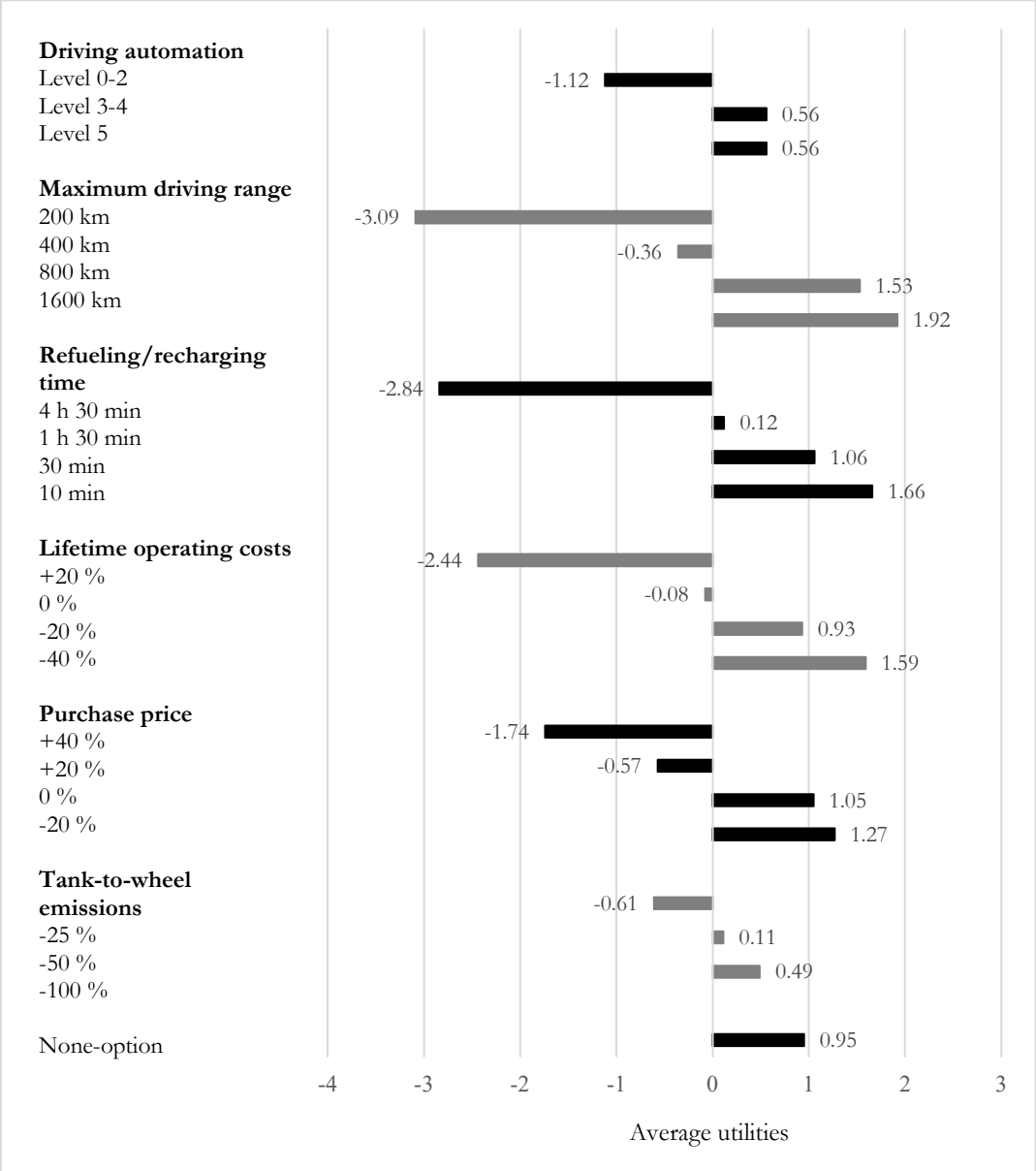

Figure 14: Average part-worth utilities of the different attribute levels

3.4.3 Shares of preference

Based on our survey results, we followed Loock (2012) and used the integrated Sawtooth market simulator to calculate the future shares of preference for autonomous and alternative fuel-powered HDTs in Germany.

First, four drivetrains were evaluated in cooperation with the expert group as foreseeable and promising alternatives to substitute diesel-powered HDTs: battery electric (BE), compressed natural gas (CNG), liquefied natural gas (LNG), and fuel cell electric (FCE). Due to the possibility of introducing diesel bans in German cities as decided by the German Federal Administrative Court in Leipzig (Bundesverwaltungsgericht, 2018), any diesel engine variants were ignored, e.g. hydrotreated vegetable oil or hybrid solutions for HDTs which combine both diesel technology and electric propulsion. Second, we specified three timeframes for the development of future scenarios as a result of the conducted expert interviews: 2020-2025, 2025-2030, and 2030-2035. The presented timeframes were evaluated as realistic cycles for the improvement of technologies and drivetrains. The projections of the realistic baseline scenario will be described in the following section.

The interviewed experts assume that current driver assistance systems level 0-2 will be the standard until 2025 followed by the implementation of automated driving systems level 3-4 between 2025 and 2030. Moreover, they refer to the availability of truck platooning which is the virtual connection of one lead truck and one or more trailing trucks that drive closely behind one another (Bhoopalam, Agatz and Zuidwijk, 2018). The ACEA (2017) distinguishes between mono-brand and multi-brand platooning. The latter allows the virtual connection of trucks from different manufacturers which is not available yet but should be possible by 2023 (ACEA, 2017). Our experts do not expect full autonomy level 5 to be available before 2035 for HDTs and state that level 3-4 will be the standard technology for a minimum of 10 years. There is no common path about the introduction of the different automated driving levels from industry or academia which is also confirmed by Simpson *et al.* (2019). The authors describe that it is not possible to forecast how quickly connected autonomous driving technologies for trucks will evolve. However, first prototypes are currently being tested, for instance, the German logistics firm DB Schenker started to test the autonomous truck Einride T-pod on public roads in Sweden in May 2019 (Einride, 2019). Another autonomous vehicle for the transportation of heavy goods was presented by Volvo Trucks in Gothenburg, Sweden

(Volvo, 2019). The maximum driving range of the four identified technologies ranges currently from 200 km for BE HDTs up to 1600 km for LNG HDTs. According to our experts, the driving range of CNG and LNG HDTs will remain the same due to the mature level of the technology. Moreover, research and development spending of truck manufacturers will focus on zero emission technologies, thus, experts assume that battery capacities will increase what leads to an average driving range of 400 km for future generations of BE HDTs. An even higher driving range might be possible but the experts point out that BE HDTs will be mainly used in urban logistics. The experts forecast the market introduction of FCE HDTs between 2025 and 2030 in Germany. Based on the latest press releases from Hyundai or Nikola Motor, an average driving range of 800 km seems to be realistic for the series production of FCE HDTs (Nikola Motor, 2018; Hyundai, 2019a). Higher driving ranges are theoretically possible when using other technologies for hydrogen storage which benefit from higher energy density, however, a hydrogen storage standard for HDTs was not defined yet. For instance, Nikola Motor focuses on 700 bar whereas Hyundai's FCE HDT is constructed for 350 bar of use (Nikola Motor, 2018; Hyundai, 2019a). While CNG, LNG and FCE HDTs can be refueled quickly, our experts estimate that recharging times for BE HDTs will be reduced drastically from an average of 4 h 30 min in 2020-2025 to only 30 min in 2030-2035 due to increasing efficiency and the availability of high-power charging points of more than 500 kW for HDVs. According to our experts, the driver and a truck's fuel costs account for the largest share of operating costs which is also described in a study by McKinsey & Company (2016). Hence, a truck's total-cost-of-ownership (TCO) decreases significantly when using HDTs equipped with automated driving technology. The study revealed that the TCO for medium- and heavy-duty trucks can be reduced by 9% when using automated driving level 4 and by 35% in case of full autonomy level 5 (McKinsey & Company, 2016). The possibility to lower operating costs when using self-driving technology has been reported by several studies, e.g. due to reduced fuel consumption (Milakis, Van Arem and Van Wee, 2017). Fritschy and Spinler (2019) argue that the delivery of products with self-driving trucks will be cheaper which leads to the additional benefit of increasing customer satisfaction. However, operating costs of alternative fuel-powered HDTs can be negatively affected by expensive fuel costs for innovative drivetrains such as hydrogen or rising electricity costs. Nevertheless, the interviewed experts agreed that hydrogen costs will be more expensive than diesel but are

likely to decrease due to rising demand from 2030 onwards. In addition, experts assume that government incentives will further help to reduce operating costs of low-emission vehicles which will be higher for electric vehicles, hence BE and FCE HDTs, compared to CNG and LNG. Thus, natural gas trucks are unlikely to benefit from lower operating costs from 2025 onwards despite the availability of level 3-4 automated driving technology. Since January 2019, natural gas and electric trucks are exempted from German highway tolls but the experts expect that the reduction of tolls will be available for electric HDTs in the future only what increases operating costs of CNG and LNG vehicles (BMVI, 2019c). Purchase prices of the identified HDTs will be initially higher compared to conventional diesel-powered HDTs, mostly due to their alternative drivetrain technologies but also because of automated driving systems but our experts assume that battery and fuel cell prices will decrease significantly over time. Moreover, costs for self-driving hardware and software will come down drastically what is in line with projections of other experts. For instance, Kevin Clark, CEO of Aptiv Plc, estimates that software and hardware equipment for self-driving vehicles cost nowadays between 70,000 and 150,000 US-Dollars but will decrease to 5000 US-Dollars by 2025 (Reuters, 2017). A truck's purchase price will therefore be affected slightly when series production of autonomous driving technology will be available which is also supported by Fagnant and Kockelman (2015) who estimate a difference of 3000 US-Dollars between conventional and autonomous vehicles in the case of mass production. Lastly, TtW emissions which describe the final fuel conversion in a truck will not change over the next years. Experts assume that the focus will be on WtT emissions that include "the energy expended and associated emissions to deliver the finished fuel in the fuel tank" (Alamia *et al.*, 2016, p. 446). Table 6 summarizes the projections and shares of preference for the realistic baseline scenario. The projections and results of the optimistic and pessimistic scenario are summarized in the appendix (Table 13 and Table 14).

Table 6: Realistic scenario 1) 2020-2025, 2) 2025-2030, 3) 2030-2035

Technology	Automated driving	Driving range	Refueling time	Operating costs	Purchase price	TtW emissions	Shares of preference
BE[1)]	Level 0-2	200 km	4 h 30 min	0 %	40 %	-100 %	3.3 %
CNG[1)]	Level 0-2	400 km	10 min	0 %	20 %	-25 %	3.9 %
LNG[1)]	Level 0-2	1600 km	10 min	0 %	20 %	-25 %	46.8 %
None[1)]							46.0 %
BE[2)]	Level 3-4	400 km	1 h 30 min	-20 %	20 %	-100 %	19.8 %
CNG[2)]	Level 3-4	400 km	10 min	0 %	20 %	-25 %	2.2 %
LNG[2)]	Level 3-4	1600 km	10 min	0 %	20 %	-25 %	44.6 %
FCE[2)]	Level 3-4	800 km	10 min	20 %	40 %	-100 %	9.8 %
None[2)]							23.6 %
BE[3)]	Level 3-4	400 km	30 min	-20 %	0 %	-100 %	22.6 %
CNG[3)]	Level 3-4	400 km	10 min	0 %	0 %	-25 %	1.6 %
LNG[3)]	Level 3-4	1600 km	10 min	0 %	0 %	-25 %	33.5 %
FCE[3)]	Level 3-4	800 km	10 min	-20 %	20 %	-100 %	35.6 %
None[3)]							6.7 %

The last column shows that truck customers will prefer LNG HDTs during the first timeframe from 2020 to 2025 despite a higher purchase price. LNG HDTs benefit especially from a high driving range and short refueling times which are the two attributes with the highest relative importances as presented in Fig. 13. Moreover, operating costs are similar to diesel-powered HDTs and TtW emissions can be reduced. BE HDTs, on the other hand, will be the least attractive alternative to truck customers in the beginning because of the short driving range, long recharging times and an expensive purchase price. The second timeframe from 2025 to 2030 reveals that truck customers still favor LNG among the different technologies, however, BE HDTs are becoming a more attractive alternative due to decreasing costs and technological development such as increasing efficiency and decreasing recharging times. It is worth noting that customers will prefer FCE HDTs over CNG HDTs despite both higher purchase prices and higher operating costs. The third timeframe, 2030 to 2035, indicates that electric drivetrains (BE and FCE) and LNG will be the most preferred options by truck customers. FCE drivetrains will be the most attractive solution followed by LNG and BE HDTs. Interestingly, the none-option which displays a conventional diesel-powered HDT is still more attractive than a CNG-powered vehicle.

3.5 Conclusion

Our study aimed to reveal how freight companies assess the attributes of autonomous and alternative fuel-powered HDTs in Germany. Furthermore, we identified four promising alternative drivetrains and developed future scenarios in cooperation with an expert group to simulate customers' preference shares for innovative HDTs.

By conducting a CBC experiment with employees from German freight companies, we found that the maximum driving range is the most important attribute followed by the refueling/recharging time. TtW emissions, on the other hand, was evaluated as the least important attribute what is in line with previous studies which criticize that environmental benefits of low-emission vehicles are not a top concern. Driving automation was assessed as less important than the purchase price or operating costs by the survey participants, however, they clearly preferred conditional and full automation to manual control.

An important conclusion which can be drawn from the results of our market simulation is the fact that freight companies are generally open to utilizing autonomous and low-emission HDTs. We therefore assume that the low adoption rate of alternative fuel-powered HDTs in Germany is not based on skepticism about alternative drives but much more on uncertainties and external variables. For instance, a clear strategy to low-emission trucking from the government is required to increase planning security for all stakeholders involved. This could lead in return to research and development expenditure on zero emission technologies from truck manufacturers, investments in a widespread recharging/refueling infrastructure, and the purchase of low-emission commercial vehicles from freight companies. Following research on the adoption of eco-innovations (e.g. Rennings *et al.*, 2006), we recommend the introduction of environmental policy instruments, financial subsidies and strict legal requirements to increase the awareness of environmental benefits of alternative drives. Anderhofstadt and Spinler (2019) describe the introduction of low-emission zones as a possibility to spur the penetration rate of low-emission HDTs in Germany. Kaplan *et al.* (2016) recommend pilot tests and campaigns to persuade fleet managers to adopt environmentally friendly vehicles which is in line with Schulte, Hart and Van der Vorst (2004) who suggest "hands-on" experience to reduce skepticism toward innovative products. The results of our market simulation indicate that LNG HDTs are an attractive and market-ready substitute for

diesel-powered trucks, however, there exist only ten LNG refueling stations across Germany as of December 2019 compared to 58 in Italy and 48 in Spain (NGVA, 2019). Hence, we suggest to financially support the construction of new LNG refueling stations as well as fast approval processes to setup a comprehensive network across the country. Moreover, Goulding *et al.* (2017) describe the possibility of using biogas in the transportation sector to further reduce the ecological impact of natural gas vehicles. In the medium- and long-run, BE and FCE trucks seem to be relevant technologies but the ACEA states that public charging points for BE HDTs do not even exist and available hydrogen refueling stations for passenger cars cannot be used by trucks due to higher hydrogen demand and missing standards (ACEA, 2019). Hence, financial incentives for freight companies in Germany such as the toll reduction for natural gas and electric trucks will not solve the current "chicken-and-egg" situation due to the missing infrastructure. We therefore recommend a coordinated way for the market development of refueling/recharging stations for alternative fuel-powered HDTs in Germany aligned with European projects. Compared to low-emission vehicles, there are no self-driving HDTs commercially available yet. However, autonomous vehicles will be reality soon and probably earlier than most people would assume (Talebian and Mishra, 2018). First prototypes are currently being tested and existing assistant systems such as active lane keeping or brake assists pave the way for vehicle automation level 3 and higher. Consequently, it seems wise to initiate required actions rather soon to ensure a smooth introduction of this disruptive technology. Fritschy and Spinler (2019) assess the impact of autonomous trucks on business models and note that neglecting to invest in autonomous trucks might lead to serious consequences in the long run for all stakeholders involved. However, there are still several barriers to the widespread diffusion of self-driving vehicles which need to be solved to leverage the advantages of the technology, among others, a consistent certification framework, insurance/liability issues, electronic security, and privacy concerns (Fagnant and Kockelman, 2015; Gkartzonikas and Gkritza, 2019). In summary, a close collaboration between truck manufacturers, customers, infrastructure companies and policymakers, aligned with European strategies, is essential to spur the penetration of both autonomous and alternative fuel-powered HDTs.

Despite the practical relevance of our experiment, the presented acceptance and use of technologies models served as helpful theories which guided the execution of our CBC

experiment. For instance, we conclude that freight companies evaluate autonomous and alternative fuel-powered HDTs as beneficial which focuses on the first predictor of TPB, the attitude toward a behavior. The second predictor, subjective norms, is another important aspect of our study due to imminent EU-wide emission limits for HDTs or the possibility of implementing diesel bans in German city centers. The fact that 58.0% of our participants had previous experience with alternative fuel-powered HDTs is relevant for the third TPB determinant, perceived behavioral control, as it considers past experiences. TAM includes two specific variables that are relevant for users to adopt or reject an innovation. The perceived ease of use displays if utilizing a new technology would be free of effort. Presented attributes such as the maximum driving range or the refueling/recharging times of alternative fuels are most important to our respondents, hence, truck manufacturers need to focus on daily practicability with respect to diesel engines as the benchmark technology. The second variable of TAM, perceived usefulness focuses on how an innovation improves a job which is related to self-driving technology of HDTs. Conditional and full driving automation can enhance and modify the job of truck drivers but also help to solve the current shortage of qualified drivers.

Our study is not without limitations. First, the availability of refueling stations/recharging points was not included as an attribute to our CBC experiment as we concentrated on truck specifications only and see a comprehensive refueling/recharging infrastructure as a prerequisite for utilizing low-emission vehicles. Second, we are aware that the defined purchase price levels of -20% to +40% relative to diesel HDTs are currently unrealistic for autonomous and alternative fuel-powered HDTs, especially in case of BE and FCE HDTs. However, we aimed to focus on the series production of low-emission HDTs and tried to avoid a dominance of purchase price over other product attributes. Thus, presenting current purchase prices could have changed the importances of our attributes. Furthermore, the comparably small sample size of 69 is another limitation of our study as the number of participants did not allow a detailed analysis and segmentation of customers. Hence, we recommend to conducting a CBC analysis with a larger sample size followed by the segmentation of truck customers in future research to test if freight companies which focus on international long-haul operations have other preferences than companies focusing on urban delivery. In addition, our study offers other interesting opportunities for future research

such as the extension and comparison to different economic/geographical areas since vehicle regulations or incentive programs differ among various countries and regions.

In comparison to the second chapter which explored the research area from a broader perspective, we were focusing on freight companies in the third chapter of this dissertation to better understand how truck customers value the main attributes of innovative HDTs. Furthermore, we developed different scenarios until 2035 in cooperation with an expert group to simulate future customers' preference shares for innovative HDTs. Our results show that fully electric drivetrains, i.e. BE and FCE HDTs, are becoming increasingly popular whereas preference shares of natural gas and conventional trucks are continuously decreasing. Due to the fact that FCE HDTs are not commercially available yet, we are focusing on BE HDTs in the fourth chapter of this dissertation to forecast the diffusion of BE HDTs in Germany considering total-cost-of-ownership reduction effects.

4. Forecasting the market penetration of battery electric heavy-duty trucks in Germany considering total-cost-of-ownership reduction effects

The following chapter is based on Anderhofstadt and Spinler (2020a) 'Forecasting the market penetration of battery electric heavy-duty trucks in Germany considering total-cost-of-ownership reduction effects' [4]

4.1 Introduction

Germany is the sixth largest emitter of carbon dioxide (CO_2) worldwide and was responsible for 2% of global CO_2 emissions in 2018 which hit a new record high of 36,573 million tons (Global Carbon Atlas, 2020). According to the United States Environmental Protection Agency (EPA), CO_2 is the primary human-driven greenhouse gas (GHG) and is mainly produced by the combustion of fossil fuels for energy and transportation (EPA, 2019). The top CO_2 producing countries are China (10,065 million tons) and the United States (5416 million tons), however, when assessing CO_2 emissions per capita, Qatar is ranked 1st (38 tons), the United States 12th (17 tons), Germany 31st (9.1 tons), and China 49th (7 tons) (Global Carbon Atlas, 2020). In November 2016, the Paris Climate Agreement entered into force which is considered a milestone in climate policy as it is the first international response to the threat of global temperature increase (UNFCC, 2019). Based on the targets of the Paris Agreement, the German government adopted the German Climate Action Plan 2050 which includes sector-specific reduction targets to reach a GHG neutral society by the middle of the 21st century. The first overall milestones is to reduce total GHG emissions in Germany by 2030 by at least 55% compared to the reference year 1990. The latest report from the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) states that total GHG emissions in Germany decreased by around 31% from 1251 million tons in 1990 to 866 million tons in 2018. The 2020 target is to emit less than 751 million tons of GHG emissions and less than 563 million tons by 2030. The energy sector is the largest producer of GHG in Germany and was responsible for 311 million tons in 2018, followed by the industry

[4] Anderhofstadt, B. and Spinler, S. (2020a) 'Forecasting the market penetration of battery electric heavy-duty trucks in Germany considering total-cost-of-ownership reduction effects', Unpublished Working Paper.

sector which accounted for 196 million tons and the transportation sector which emitted 162 million tons. While emissions from the energy sector fell by 33.4% and emissions from the industry sector by 30.7% compared to 1990, emissions from transportation decreased by 0.9% only. By 2030, the German Climate Action Plan specifies a reduction target of 40% from transportation compared to 1990. Passenger cars (60.6%) and commercial vehicles (35.6%) are by far the largest emitters of GHG emissions from transportation in Germany. According to the BMU, the main reasons for emissions from transportation are higher vehicle and ton kilometers travelled, the use of fossil fuels and high average CO_2 emissions per vehicle (BMU, 2019). This is further supported by statistics from the European Environment Agency (EEA) showing that average emissions from new passenger cars in Europe increased from 118.1 grams CO_2 per kilometer in 2016 to 120.4 grams in 2018 (EEA, 2019). In Germany, new cars registered equipped with alternative drives had a growth rate of 54.3% from 2017 to 2018 (BMU, 2019). According to the German Federal Transport Authority (KBA), 47 million cars are currently registered in Germany of which around 900,000 (1.9%) are powered by alternative fuels (LPG, CNG, hybrid, electric). On the other hand, only 246 (0.07%) of 341,154 registered heavy-duty trucks (HDTs) run on alternative drive technologies as of January 2019 (KBA, 2019). According to the statistics from the KBA, 99.7% of registered HDTs run on diesel although the German Federal Administrative Court in Leipzig decided in February 2018 that diesel bans are possible to reduce harmful emissions in German cities (Bundesverwaltungsgericht, 2018; KBA, 2019). In addition, the European Commission (EC) adopted the first-ever CO_2 emission standards for heavy-duty vehicles (HDVs) in the European Union in August 2019 and plans to reduce around 54 million tons of CO_2 from 2020 to 2030. By 2025, HDV manufacturers will have to achieve a 15% reduction of fleet-wide average CO_2 emissions compared to the defined reference period from July 2019 to June 2020. A reduction target of 30% is currently set from 2030 onwards but will be reassessed during the regulation review in 2022 (EC, 2019).

Different technologies and alternative fuels exist to reduce emissions from HDTs but battery electric (BE) trucks are currently the only viable option for locally emission-free road freight transportation. While BE light-duty trucks and commercial vans are becoming increasingly popular in Germany, BE HDTs remain exotic. As of January 2019, only 21 fully electric HDTs were registered in Germany compared to 16,420 fully electric light-duty trucks and commercial

vans with a maximum payload capacity of 999 kg. Recently, large European truck manufacturers such as Volvo, DAF, MAN and Daimler introduced their first BE HDTs. The Swedish truck manufacturer Volvo states on its website that "electromobility is playing a key role in our move towards sustainable transportation. Electric trucks are now becoming a reality and a viable commercial solution for cities and businesses" (Volvo, 2019). MAN and Daimler, the two largest German truck manufacturers, are also opting for an electric future. MAN explains on its website that "a vision becomes reality: the urban distribution transport of tomorrow is virtually silent and emission-free. With the new electric truck we are ready to set off into a sustainable future" (MAN, 2019) and Daimler describes itself as the technological leader which "intends to shape the logistics and passenger transport of tomorrow - with electric solutions that deliver the maximum benefit for customers and the environment" (Daimler, 2019).

Thus, BE HDTs are currently the most effective solution for truck manufacturers to achieve European CO_2 targets and are an immediate opportunity for freight companies to avoid imminent diesel bans in Germany city centers. Nevertheless, only 21 BE HDTs are currently registered in Germany operated by a few innovative firms. Due to an increasing number of available BE truck models, decreasing costs, an increasing level of environmental awareness in the society, and strict legal requirements, the number of BE HDTs in Germany is going to rise over the next decades, especially in case of city distribution and short-haul transportation. Based on the adoption rate of BE HDTs, we will identify specific policy incentives which can help to spur the penetration of BE HDTs in Germany in order to accelerate the market diffusion. However, certain aspects such as long recharging times, a restricted driving range and the total-cost-of-ownership (TCO) need to be considered carefully. The main purpose of this study is therefore to forecast the diffusion of BE HDTs in Germany, described by the following research question:

What will be the market diffusion of battery electric heavy-duty trucks in Germany considering total-cost-of-ownership reduction effects?

To our knowledge, this is the first attempt which combines the Generalized Bass diffusion model (GBM) and a thorough TCO analysis of BE and diesel-powered HDTs, guided by Rogers's theory of innovations and the different adopter categories. Hence, the final aim of

this study is to forecast the diffusion of BE HDTs in Germany considering TCO reduction effects. The GBM is a modified version of the traditional Bass diffusion model (BM) as it includes also external variables which affect the market penetration of a new product, e.g. decreasing costs or marketing effects. The next section gives an overview of BE HDTs in Germany including technical specifications, followed by the diffusion of innovations theory. The methodological process will be explained in the third section. Thereafter, we present and discuss the results of our study before concluding it.

4.1.1 Market overview: battery electric heavy-duty trucks

All kind of battery electric vehicles use onboard battery packs to store electric energy which can be recharged at private or public charging points (Kluschke *et al.*, 2019). Compared to battery electric (BE) passenger cars (e.g. Tesla Model 3, BMW i3, Renault Zoe) and BE light-duty commercial vehicles (e.g. Streetscooter Work, VW e-Crafter, Mercedes eVito), BE HDTs are rarely seen on German roads despite the fact that various truck manufacturers recently introduced innovative and environmental-friendly vehicles. Some BE HDTs are already in operation, for instance, the German automobile manufacturer Porsche utilizes the MAN eTGM for its logistics processes in Stuttgart which saves up to 30 tons CO_2 per year (Porsche, 2018). In 2017, the BMW Group expanded its electric truck fleet in Munich and operates three 40 ton BE HDTs which reduce CO_2 emissions by 82 tons annually (Margaritis *et al.*, 2016; BMW, 2017a). Another 40 ton BE truck with a refrigeration unit is used by the supermarket chain ALDI in the German Ruhr area since 2018 (ALDI, 2018). Table 7 gives an overview of some BE models from the largest European truck manufacturers and their technical specifications. Apart from the well-known European manufacturers presented in Table 7, there are also small manufacturers such as E-Force from Switzerland or Framo eTrucks from Germany which buy diesel-powered HDTs and convert them to BE vehicles (Anderhofstadt and Spinler, 2019).

Table 7: Battery electric heavy-duty trucks

Manufacturer	Model	Battery capacity	Driving range	GVW*	Source
DAF/VDL	CF Electric	170 kWh	100 km	37 tons	(DAF, 2019)
MAN	eTGM	185 kWh	200 km	26 tons	(MAN, 2019b)
Mercedes	eActros	240 kWh	200 km	25 tons	(Daimler, 2018c)
Volvo	FE Electric	300 kWh	200 km	27 tons	(Volvo, 2018b)

*GVW = Gross Vehicle Weight

4.2 The diffusion of innovations and adopter categories

The transition to a GHG neutral transportation sector requires the diffusion of locally emission-free vehicles including BE trucks for shuttle transportation and city distribution. In this study, we are applying the GBM to forecast the diffusion of BE HDTs in Germany which, unlike other forecasting methods, follows Rogers' diffusion of innovations theory (Parker, 1994). Moreover, the theory has been previously applied to study the diffusion of alternative fuel-powered vehicles and therefore serves as the guiding theory of our study. For instance, a recent study by Lee, Hardman and Tal (2019) follows Rogers' diffusion of innovations theory to analyze what groups adopt plug-in electric vehicles in California and apply the BM to forecast the market diffusion of the vehicles.

Regardless of whether the theory will be applied at the individual or firm level, the adoption process of innovations is usually difficult, even when a new idea provides obvious benefits to its customers and society. Karakaya, Hidalgo and Nuur (2014) describe the special case of eco-innovations such as renewable energy technologies or innovative pollution prevention schemes and note that empirical evidence has proven that especially environmental innovations require a long time before reaching a relevant number of adopters in the system. Moreover, it often takes several years from the moment a new product becomes available until its widespread diffusion (Rogers, 1983). The Schumpeterian trilogy describes the following three phases of product creation and technological change: (i) invention: generating a new idea, (ii) innovation: developing the generated idea, and (iii) diffusion: spreading the innovation across potential markets (Stoneman and Diederen, 1994). Rogers (1983, p. 5) defines diffusion as "the process by which an innovation is communicated through certain channels over time among the members of a social system". His definition includes the four

main aspects which are identifiable in all diffusion processes: "innovation", "communication channels", "over time", and "among the members of a social system". The process of product adoption over time allows to categorize the different types of adopters of an innovation. The number of adoptions can be utilized to plot either the bell-shaped frequency curve or the cumulative S-shaped curve (see Fig. 27 in the appendix). The S-shaped diffusion curve starts to rapidly increase after 10-25% of system members adopted the new product, hence, this phase is also known as the "heart of the diffusion process" as it is crucial for the future diffusion process (Rogers, 1983, p. 245).

An important part of the diffusion of innovations theory is the categorization of adopters that are mainly influenced by their individual innovativeness, defined as "the degree to which an individual or other unit of adoption is relatively earlier in adopting new ideas than other members of a social system" (Rogers, 1983, p. 245). The term "innovativeness" used in Rogers' diffusion of innovations theory is closely linked to the BM which uses the imitation and innovation coefficients as two main parameters to forecast new product diffusion. The categorization of adopters usually follows normality and the mean as well as the standard deviation can be applied to divide the normal distribution into five adopter categories: (1) *innovators*, (2) *early adopters*, (3) *early majority*, (4) *late majority*, and (5) *laggards*. The first category in the bell-shaped frequency curve, *innovators*, represents the first 2.5% of new product adopters. This group immediately wants to try innovative ideas and is able to understand new complex technologies, however, they are also willing to accept a high degree of uncertainty as innovations often prove to be less beneficial as previously expected. Hence, innovators need the financial power to cope with unsuccessful products but they play a key part in the diffusion process since they act as a gatekeeper to the rest of the social system. For instance, Kaplan *et al.* (2016) refer to the example of DHL, the largest logistics company in the world, and Streetscooter, an innovative small manufacturer of affordable electric delivery vehicles. Due to a lack of alternatives from established truck manufacturers, DHL acquired the university spin-off Streetscooter in 2014 to reduce road traffic emissions of its fleet (DHL, 2014). BMW can be named as another innovator considering the use of BE trucks in Germany. As previously described, the German automobile and motorcycle manufacturer started the operation of an electric 40-ton HDT in Munich in 2015 and expanded its fleet by two additional BE HDTs for its Munich plant in 2017 (Margaritis *et al.*, 2016; BMW, 2017a). Both

companies reflect the main characteristics of innovators such as the ability to understand new technologies as well as the financial power to cope with possible financial losses. Besides, Triguero, Moreno-Mondéjar and Davia (2016) note that technological leader firms are usually ahead to their competitors in terms of profit, productivity or market value. *Early adopters* are the next 13.5% of adopters of a new product. They have an important opinion leadership role as other potential adopters seek for their feedback about the innovation before purchasing it themselves. Thus, early adopters try to reduce uncertainties toward a new product by presenting a subjective assessment of it. For instance, the American logistics company UPS, a top competitor of DHL, announced in January 2020 that they have invested in the London based start-up Arrival which produces electric vehicles. In addition, UPS orders 10,000 electric vehicles with priority access from the company to accelerate its fleet electrification strategy (UPS, 2020). The next 35% are defined as the *early majority* and utilize new products before the average user. Due to a relatively long decision period whether to adopt an innovation or not, they do not hold a leadership position but act as an important link between the early and late adopting categories. The *late majority* uses innovations after the average adopters and represent the following 35% of the bell-shaped frequency curve. They are usually skeptical toward new technologies and adopt them because of economic reasons and rising pressure from their network. Subjective norms is one of three predictors in the theory of planned behavior by Ajzen (1991). Anderhofstadt and Spinler (2020) state that subjective norms could be pressure from the government, society or customers to switch to environmental-friendly innovations such as alternative drivetrains. Due to the relatively low financial power of the late majority, they adopt an innovation as soon as its uncertainties have been removed. The last category is represented by *laggards* who are the last 16% of adopters. Laggards focus on the past and are embedded in a similar thinking network, hence, decisions are usually based on what has been used by previous generations. Thus, it may happen that another innovation, e.g. self-driving technology for trucks, is already on the market when laggards adopt a new product (Rogers, 1983).

4.3 Research methodology

4.3.1 Generalized Bass diffusion model

The parsimonious Bass diffusion model (BM) was developed by Bass (1969) and is one of the most popular and widely applied models to forecast the diffusion curve of new products and technologies. The traditional BM focuses on durable products and contains three key variables: innovators *p*, imitators *q*, and the number of potential adopters *m* (Bass, 1969; Boswijk and Franses, 2005). The main assumption of the model is that the adoption of a new product at time *T* is based on the purchase probability by innovators and imitators (Bass, 1969). The first variable, innovators *p*, is often referred to as "external influence" and describes members in a system that decide independently from others whether to adopt a new technology or not, similar to the definition of innovators by Rogers (1983). On the other hand, imitators *q* are frequently described as "internal influence" that are affected by the decisions of others in the system and learn from those who have already adopted the new product defined as early and late majority by Rogers (1983) (Bass, 1969; Bass, Krishnan and Jain, 1994). Thus, the purchase probability by innovators is primarily affected by mass media and advertisement whereas the purchase probability by imitators is influenced by word-of-mouth communication and pressure from previous adopters and sales represented by *F(T)* (Mahajan, Muller and Bass, 1990). Based on the described variables, Bass (1969) arrived at the following mathematical expression to forecast sales at time *T* defined as *f(T)*:

[1] $$f(T) = p * m + (q - p) * F(T) - \frac{q}{m} * F(T)^2$$

In the following years the traditional BM was criticized as incomplete by researchers and economists as it does not include contagion effects and economic variables. Hence, Bass, Krishnan and Jain (1994) extended the traditional BM and proposed a modified version of it, the generalized Bass diffusion model (GBM). The authors argue that certain decision variables such as price or advertising can affect the adoption curve of technological innovations and included the mapping function *x(T)* which incorporates the effect of pre-defined decision variables (Bass, Krishnan and Jain, 1994):

[2] $$f(T) = \left(p + \frac{q}{m} + F(T)\right) * \left(m - F(T)\right) * x(T)$$

In this study, we are applying the GBM to forecast the market penetration of BE HDTs in Germany. Following previous studies on alternative fuel-powered commercial vehicles (e.g. Seitz, Beuttenmüller and Terzidis, 2015; Bubeck, Tomaschek and Fahl, 2016; Anderhofstadt and Spinler, 2019), we consider the vehicle's TCO as the most important external variable for truck customers whereas private customers are usually more concerned about the initial investment, the purchase price of the car (Sierzchula *et al.*, 2014). For instance, Park, Kim and Lee (2011) utilized a purchase price reduction of 3% between hydrogen fuel cell (FC) cars and conventional cars as an external variable to forecast the number of hydrogen FC cars in Korea. The effectiveness of the external decision variable will be described by β_1 (Benvenutti, Ribeiro and Uriona, 2017). Thus, we follow a similar process as Park, Kim and Lee (2011) but focus on the TCO difference between diesel-powered HDTs and BE HDTs instead of the purchase price of the vehicles only. We define the following mapping function which will then be implemented in the introduced GBM equation:

[3] $$x(T) = 1 + \beta_1 \frac{TCO(T) - TCO(T-1)}{TCO(T-1)}$$

where

[4] $$TCO(T) = \frac{TCO_{\ BE\ HDT}}{TCO_{\ Diesel\ HDT}}$$

The GBM was chosen as the method of choice due to the following reasons. First, both GBM and BM can be used to forecast the diffusion process of innovations from different industries, e.g. consumer durable goods, medical equipment, agriculture, and telecommunications (Parker, 1994). Moreover, the GBM will be reduced to the traditional BM if decision variables are constant for all *T* what leads to a certain level of consistency. The closed-form of the GBM also helps to better understand the behavior of it in the time domain (Bass, Krishnan and Jain, 1994). In addition, the GBM has been frequently applied in recent years to forecast the diffusion process of alternative fuel-powered vehicles. For instance, Park, Kim and Lee (2011) developed a forecasting model for FC cars in Korea considering an increasing number of hydrogen stations and decreasing purchasing prices. Li, Ma and Li (2017) applied the GBM focusing on electric vehicles including charging stations in China. Benvenutti, Ribeiro and Uriona (2017) used the GBM to forecast the long-term diffusion of alternative fuel-powered passenger cars in Brazil. Another relevant study was conducted by Massiani and Gohs (2015)

who investigated the choice of adequate Bass coefficients for new automotive technologies with a focus on electric vehicles. However, certain aspects need to be addressed carefully when applying the model. For instance, we have limited insights into the choice behavior of imitators and innovators when applying the model (Massiani and Gohs, 2015). Moreover, Lee *et al.* (2006) criticize that the model has certain limitations when forecasting the adoption of new products which are not yet available on the market. Hence, researchers face the difficulty of finding appropriate products with similar characteristics which are already available for a certain period of time. Furthermore, the parameters of the model rely on historical demand and the choice of appropriate data requires a careful and critical selection which will be further demonstrated in the following section.

4.3.2 Estimation of model parameters

The careful selection of reliable model parameters is an essential task when applying the GBM. In order to forecast the diffusion curve of BE HDTs in Germany considering decreasing costs, we need to define the following parameters: (1) the market potential *m*, (2) the innovation factor *p*, (3) the imitation factor *q*, and (4) the annual expected TCO decrease of BE HDTs compared to diesel-powered vehicles in Germany *TCO(T)* including β_1.

4.3.2.1 Market potential

The market potential *m* is often defined equal to the number of households or companies in the country or region analyzed and multiplied by certain values to present different growth scenarios (Massiani and Gohs, 2015). Other than previous research forecasting the diffusion of alternative fuel-powered vehicles (e.g. Park, Kim and Lee, 2011), we do not assume that the truck market will be completely replaced by one type of drivetrain technology. According to Anderhofstadt and Spinler (2019), there are three promising drivetrains which have the potential to reduce emissions from diesel-powered HDTs: battery electric, compressed or liquefied natural gas as well as hydrogen fuel cell electric trucks. However, the authors criticize the current prototype stadium of FCE trucks and note that natural gas may be a mature technology but "is still a fossil fuel which will not help to reach the set CO_2 reduction targets" (Anderhofstadt and Spinler, 2019, p. 101). Sen, Ercan and Tatari (2017) compared different

HDT drivetrains and concluded that CNG-powered trucks can emit even more emissions than conventional ones. This is especially important as the German Federal Administrative Court in Leipzig decided in 2018 that German cities are allowed to ban polluting vehicles to reduce harmful emissions (Bundesverwaltungsgericht, 2018). Thus, BE HDTs are currently the only viable option for locally emission-free transportation but have the downside of higher costs, a limited driving range and long recharging times. Accordingly, it seems unrealistic to assume that all registered HDTs could be replaced by BE HDTs in Germany, in particular for long-haul operations. As of January 2019, 341,154 HDTs were registered in Germany and forecasts commissioned by the German Federal Ministry of Transport and Digital Infrastructure (BMVI) reveal that road transportation will increase by 0.8% annually until 2030 what leads to 372,405 HDTs registered by 2030 (BMVI, 2014; KBA, 2019). To our knowledge, there is no public information about the average mileage driven per HDT in Germany and we are therefore relying on information provided by the product management department of a leading European truck manufacturer which demonstrate that 45% of HDTs in Germany run less than 265 km daily. Moreover, Andy Illgen, CEO of Framo eTrucks, commented in an interview that half of all trucks drive less than 150 km per day, however, he does not refer to a specific weight category (Eurotransport, 2018). Accordingly, we assume a rounded market potential m of 168,000 BE HDTs in this study.

4.3.2.2 Innovation factor and imitation factor

The next parameters which need to be defined are the innovation factor p and imitation factor q, however, there are different methods for estimating both factors. Some authors use p and q coefficients as cited in previous studies whereas others calculate values of one market to apply them for another which can be related to technologies or different geographical regions. For instance, Park, Kim and Lee (2011) estimate p and q to forecast hydrogen FC vehicles in Korea based on historical sales of hybrid electric vehicles in Japan. Due to a lack of electric vehicle sales data in Denmark, Jensen *et al.* (2017) utilize Norwegian registration numbers for their diffusion model. However, transferring parameters based on other technologies or geographical regions can be incorrect due to higher or lower product demand in one country compared with another unless market differences result from a different product supply only. It is therefore recommended to use data from the same country and an equivalent technology

as the ones researchers want to analyze (Massiani and Gohs, 2015). For instance, Lamberson (2008) was in a privileged situation to use historical monthly registration data of hybrid electric vehicles in the United States from 2001 to 2007 to forecast their diffusion in the United States.

Lilien, Rangaswamy and Van den Bulte (2000) recommend a minimum of four historical periods to obtain reliable *p* and *q* values. As such reliable historical sales numbers of BE HDTs in Germany do not exist, we are using available information on battery electric passenger cars (BEVs) in Germany to rely on data from the same technology and the identical market. Moreover, both BEVs and BE HDTs benefit from similar advantages over conventional vehicles in Germany. For instance, there is a purchase grant of 4,000 Euros as well as an exemption from motor vehicle tax for BEVs and, on the other hand, a purchase grant of 40,000 Euros and an exemption from German road tolls for BE HDTs (BMVI, 2018; BMWi, 2020). We are therefore following recommendation (ii) of Lilien, Rangaswamy and Van den Bulte (2000) who state that the BM can be applied best under two conditions to define missing Bass coefficients: (i) a new product is available on the market and historical sales data can be used or (ii) the product analyzed was not yet comprehensively introduced to the market but sales data of a similar product/technology exist. Thus, in order to calculate *p* and *q* values, we are using monthly registration numbers of BEVs in Germany from 2010 to 2019 provided by the KBA, the German Federal Transport Authority. Fig. 15 shows the historical new monthly BEV registrations in Germany which have increased from 17 new registrations in January 2010 to 5880 in September 2019 (KBA, 2020a). So far, the highest number of new monthly registrations was in March 2019 with a total of 6616 BEVs.

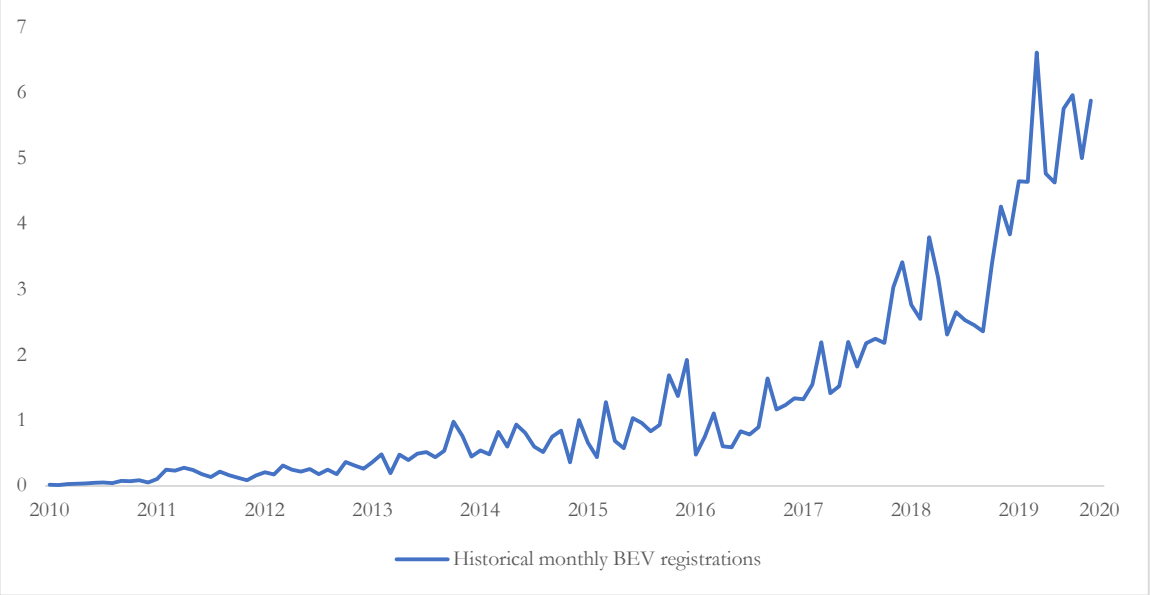

Figure 15: Historical monthly BEV registrations in Germany from 2010 to 2019 (in thousands)

We applied the nonlinear least squares approach to estimate valid Bass parameters based on the presented historical registration numbers. According to Mahajan and Sharma (1986), the NLS method is considered to provide better predictions than the maximum likelihood estimation which is also in line with findings from Massiani and Gohs (2015) who describe that NLS is the preferred method of choice in the diffusion literature. The results of our *p* and *q* analysis depend on the defined market potential *m*. We assume the ultimate market potential of BEVs to be 47 million cars which equals a 100% market share in Germany. For instance, Michael Jost, Chief Strategy Officer of the world's largest automobile manufacturer Volkswagen said that the company will launch the last generation of cars equipped with traditional combustion engines in 2026 due to their strategy shift toward BEVs (Reuters, 2018). Nevertheless, we also present the calculated *p* and *q* values for different market potentials (5 million to 47 million vehicles) in Table 8. Fig. 16, on the other hand, shows the cumulated historical monthly BEV registrations (blue line) compared to our estimated monthly BEV registrations (red dotted line) in Germany based on the calculated *p* value of 0.000008, a *q* value of 0.43, and an ultimate market potential *m* of 47 million vehicles. The cumulated diffusion of both lines is almost identical as illustrated in Fig. 16.

Table 8: Estimated p and q values for different market potentials

	47 mio	35 mio	25 mio	15 mio	10 mio	5 mio
Bass p value	0.000008	0.000011	0.000015	0.000025	0.000036	0.000069
Bass q value	0.43	0.43	0.43	0.43	0.43	0.44

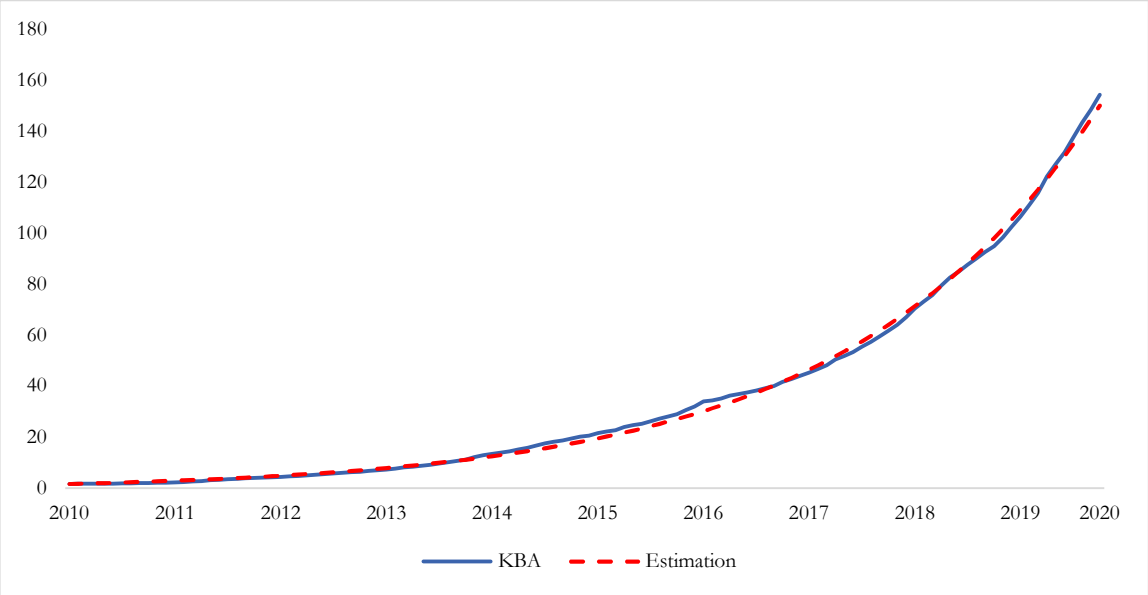

Figure 16: Historical and estimated number of cumulated BEV registrations in Germany (in thousands)

Fig. 28 in the appendix shows the estimated future diffusion curve of BEVs in Germany from 2020 to 2050 based on the final parameters. According to our calculations, the cumulative number of BEV registrations will increase to 1.3 million by 2025 and to 7 million by 2030 in Germany. Our predictions are therefore in line with the German Federal Ministry of Transport and Digital Infrastructure (BMVI) aiming for 300,000 charging points and 10 million electric cars (including hybrids) on the roads by 2030 (BMVI, 2019a).

4.3.2.3 TCO analysis of diesel and battery electric heavy-duty trucks

Compared to BE passenger cars, research on BE commercial vehicles is still young, in particular with respect to HDTs and occurring costs. We therefore gathered data from different sources such as research papers, national reports and existing BE HDTs for our

TCO analysis. Our findings were then validated by two experts from a German automobile manufacturer who are responsible for the company's "Green Logistics Strategy" and have already successfully integrated several BE HDTs into the company's supply chain. To define *TCO(T)* which is part of the mapping function, we compare the costs of BE and diesel HDTs and evaluate how costs of both technologies will change over time. We follow Benvenutti, Ribeiro and Uriona (2017) and utilize a β_1 of -1.1521 based on Park, Kim and Lee (2011) which is a negative value as decreasing costs have a positive effect on the diffusion of electric vehicles. Compared to privately owned passenger cars, our cost analysis follows the reasoning of Lebeau *et al.* (2015) who argue that rational fleet managers need to consider all costs of a vehicle and not only the purchase price. This is also supported by findings reported by Anderhofstadt and Spinler (2019) who studied factors affecting the purchasing decision and operation of alternative fuel-powered HDTs in Germany and state that the TCO is typically the most important aspect to truck customers. Based on semi-structured interviews with the introduced expert group and previous studies on BE vehicles (e.g. Lebeau *et al.*, 2015; Tanco, Cat and Garat, 2019; Van Velzen *et al.*, 2019), we include the following parameters to our TCO analysis: (1) purchase price, (2) fuel/electricity costs (including AdBlue for diesel HDTs), (3) service and maintenance costs, (4) road tolls, and (5) resale value. We follow Kühnel, Hacker and Görz (2018) and ignore costs that have no impact on the drivetrain and are therefore identical such as insurance costs or truck driver wages. Another cost component of battery electric vehicles is the required charging infrastructure. The European Automobile Manufacturers Association (ACEA) claims for 26,000 high-power public charging points for BE trucks by 2025/2030 across the EU (ACEA, 2019) but previous research assumes private charging at the depot in case of BE commercial vehicles which was also named as the preferred alternative by our expert group despite additional costs for setting up private charging points. For instance, owners can benefit from lower industrial electricity prices at their own depot compared to public charging points. Moreover, the main field of application for BE HDTs will be short-haul trucking, shuttle transportation and/or city distribution, hence, vehicles can be perfectly charged during freight loading and unloading which requires no detours or additional breaks. Furthermore, freight companies and their customers prefer overnight charging at the depot to avoid theft of the truck or the freight loaded. However, public charging for several BE HDTs would require huge premises close to city boundaries which

are either not available or very expensive. Lastly, the time to recharge the battery of a truck can take several hours due to missing high-power charging points of more than 500 kW and battery capacities of more than 200 kWh, e.g. the Mercedes eActros truck has a battery capacity of 240 kWh compared to 37.9 kWh in the all-electric BMW i3 (Daimler, 2018c; BMW, 2020). Thus, we assume industrial electricity prices based on private charging at the depot for our cost analysis but follow Lebeau *et al.* (2015) and exclude investments in setting up a private charging infrastructure as those costs strongly depend on the number of electric vehicles, the preferred maximum charge rate, potential reconstruction works on the property and the current energy supply.

We apply the traditional present discounted value formula to better compare all costs of diesel and BE HDTs with *i* describing the discount rate which is set at 2% following a recent study by Löbberding and Madlener (2019). In order to calculate the *TCO* for both drivetrains, we include the purchase price *PP*, the cost of operation *CO* in year *t* as well as the truck's resale value *RV*. In line with Tanco, Cat and Garat (2019) who conducted a break-even analysis for electric trucks, we do not apply the discounted value formula for the purchase price as we consider it a one-time investment at the beginning. Based on Kühnel, Hacker and Görz (2018), the expected life cycle of both trucks is five years before selling the vehicle.

[5] $$TCO = PP_0 + \sum_{t=1}^{n} \frac{CO_t}{(1+i)^t} - \frac{RV_n}{(1+i)^n}$$

Purchase price: the purchase price of a diesel-powered HDT tractor in Germany (e.g. MAN TGX or Mercedes Actros) is around 110,000 Euros (excluding VAT) based on the latest HDV catalog which contains prices and technical specifications of more than 3000 trucks and buses collected by the DEKRA, the German Motor Vehicle Inspection Association (ETM, 2017). A price of 110,000 Euros for a state-of-the-art diesel-powered truck was also used by Earl *et al.* (2018). On the other hand, official prices for BE HDTs in Germany were not publicly available at the time of writing, however, Framo eTrucks CEO Andy Illgen stated in an interview that the purchase price of BE trucks is two to three times higher compared to its diesel-powered counterpart (Eurotransport, 2018). In addition, the German freight companies Rhenus and Contargo tested three different BE HDTs (DAF CF Electric, Framo and E-Force) and according to Sascha Haehnke, CEO of Rhenus Trucking, the vehicles cost three times more than conventional trucks which was also confirmed by our experts (DVZ, 2019).

Accordingly, we use a purchase price of 330,000 Euros for a BE HDT. We follow Tanco, Cat and Garat (2019) and expect purchase prices of diesel trucks to increase by 3% annually from 2020 onwards and prices of BE trucks to decrease by 3% due to mass production and a drop in battery prices.

Cost of operation: the cost of operation strongly depends on the annual mileage of the vehicle. Due to the limited driving range of BE HDTs but the opportunity of recharging during loading and unloading, we are calculating with an average daily driving range of 265 km and 250 business days per year. Anderhofstadt and Spinler (2019) state that fuel and electricity costs account for the largest share of a truck's TCO. According to the ADAC, the largest automobile club in Europe, the average price per litre diesel was 1.07 Euros (excluding VAT) in December 2019 in Germany (ADAC, 2019). In its 2030 traffic forecast, the German Ministry of Transport expects fuel prices to increase to 2.10 Euros by 2030 to tackle global warming which equals a price of 1.77 Euros excluding VAT and an annual average increase of 0.07 Euros per litre from 2020 to 2030 (Reuters, 2019). Based on the latest HDV catalog, the average diesel consumption is 33.8 litres per 100 km in case of a state-of-the-art diesel-powered HDT (ETM, 2017). A report for the International Council on Clean Transportation (ICCT) states that the average consumption of European HDTs can be reduced by more than 30% to 23.9 litres per 100 km by 2030 due to certain efficiency measures (Ricardo, 2017). Diesel-powered trucks are also equipped with an additional AdBlue tank to reduce nitrous oxide emissions. According to Kühnel, Hacker and Görz (2018), AdBlue costs for HDTs will rise from 0.006 Euros per km to 0.008 Euros per km. Electricity costs for BE HDTs are more uncertain, we are therefore following Funke, Plötz and Wietschel (2019) and utilize the current industrial electricity price of 0.18 Euros per kWh for private charging of commercial electric vehicles at the depot (BDEW, 2019). Renewable energy plays a growing role in Germany as the country aims to increase the share of renewable energies from 38% in 2018 to 40-45% by 2025 and to 65% by 2030 (BMWi, 2019a). A study commissioned by the German Ministry for Economic Affairs (BMWi) estimates that energy costs will increase by 25% from 2020 to 2025 and to decrease afterward by 1% annually until 2030 due to a lower surcharge for Germany's renewable energy program (EEG) (Prognos, 2014). A decreasing EEG surcharge during the 2020s and lower electricity prices were also forecasted by Bubeck, Tomaschek and Fahl (2016) as well as McKinsey (2017). Following Kühnel, Hacker and Görz

(2018), the average consumption of BE HDTs will be 1.6 kWh per kilometer in 2020 which will be reduced to 1.25 kWh per kilometer by 2030. Another cost driver is road toll for HDVs which has been charged since January 2005 in Germany. HDTs with a state-of-the-art diesel engine (Euro VI category) are currently charged 0.187 Euros per km on highways and freeways (Toll Collect, 2019). Based on historical toll charges from 2005 to 2020, we are calculating with an average price increase of 5% annually until 2030. As BE HDTs will be mainly used for shuttle transportation and city distribution, we assume in our analysis that both technologies drive 40% on toll roads and 60% on toll-free roads. Previous research indicates that BEVs benefit from lower service and maintenance costs which applies to BE HDTs, too. According to Kühnel, Hacker and Görz (2018), there will be no considerable increase of service and maintenance costs for both vehicle types until 2030. The authors calculate with average service and maintenance costs of 0.14 Euros per km in case of diesel-powered HDTs and 0.11 Euros per km for BE HDTs.

Resale value: Davis and Figliozzi (2013) as well as Tanco, Cat and Garat (2019) utilize a resale value of 20% for diesel and BE trucks based on a ten years life cycle. Due to the defined life cycle of five years in our study as suggested by Kühnel, Hacker and Görz (2018), we are expecting a resale value of 40%. We have validated the proposed resale value of 40% by comparing current prices on the German online marketplace "www.mobile.de" for vehicle purchasers and sellers. The median resale value for diesel-powered truck lorries (MAN TGX or Mercedes Actros, first registration: 2014-2016, mileage: 200,000-300,000 km) was around 42,000 Euros (excluding VAT) based on 316 vehicles for sale in January 2020.

Table 9 and Table 10 summarize in an exemplary way the results of our TCO analysis for BE and diesel HDTs operated for five years from 2020 to 2024. Our calculations show that costs per km for BE HDTs are 1.12 Euro compared to 0.81 Euro for diesel-powered HDTs. Based on the described cost forecast, we expect the TCO gap of BE HDTs relative to diesel HDTs to decrease on average by 3.4% annually. In order to compensate potential shortcomings of BE HDTs such as a shorter driving range or long recharging times, we assume that BE HDTs will have a certain TCO advantage over diesel-powered HDTs in the future which will not exceed 20% in the long run. Based on our analysis, TCO parity will be reached by 2027 and the 20% TCO benefit by 2034. Hence, we assume the TCO gap between BE and diesel HDTs

to be stable as soon as the TCO of BE HDTs will be 20% cheaper as the TCO of diesel-powered trucks.

Table 9: TCO of battery electric HDT (2020-2024)

Mileage per business day	265 km				
Business days p.a.	250 days				
Factor/Year	**2020**	**2021**	**2022**	**2023**	**2024**
Purchase price (Euro)	330,000				
Electricity price (Euro/kWh)	0.18	0.19	0.20	0.21	0.22
Consumption (kWh/km)	1.60	1.60	1.60	1.60	1.60
Road toll (Euro/km)	0.187	0.20	0.21	0.22	0.23
Service & Maintenance (Euro/km)	0.11	0.11	0.11	0.11	0.11
Resale value (Euro)					132,000
TCO (Euro)	**370,284**				
Cost per km (Euro)	**1.12**				

Table 10: TCO of diesel-powered HDT (2020-2024)

Mileage per business day	265 km				
Business days p.a.	250 days				
Factor/Year	**2020**	**2021**	**2022**	**2023**	**2024**
Purchase price (Euro)	110,000				
AdBlue (Euro/km)	0.006	0.006	0.007	0.007	0.007
Diesel price (Euro/litre)	1.07	1.14	1.21	1.28	1.35
Consumption (litre/100 km)	33.8	33.8	33.8	33.8	33.8
Road toll (Euro/km)	0.187	0.20	0.21	0.22	0.23
Service & Maintenance (Euro/km)	0.14	0.14	0.14	0.14	0.14
Resale value (Euro)					44,000
TCO (Euro)	**269,104**				
Cost per km (Euro)	**0.81**				

It is important to note that the German Ministry of Transport and Digital Infrastructure (BMVI) announced to provide a purchase subsidy of 40,000 Euros for electric (BE and FCE) HDTs in June 2018 to narrow the gap between traditional and innovative drivetrains (BMVI, 2018). The funding guideline currently runs throughout 2020 but there was no information about extending the subsidy scheme at the time of writing, however, electric trucks are also exempted from German road tolls since January 2019 for an unlimited period. Due to uncertainties concerning future costs and potential incentives, we decided not to include temporary subsidies in our TCO calculations and follow Park, Kim and Lee (2011) and

Benvenutti, Ribeiro and Uriona (2017) who display potential changes in a sensitivity analysis which will be further described in section 4.1.

4.4 Results and discussion

In order to forecast the market penetration of BE HDTs in Germany, we need to implement the estimated parameters in the GBM equation. The final model parameters derived from the third section of this study are summarized in Table 11.

Table 11: Estimated GBM parameters

Parameters	m	p	q	TCO(T)	β_1
Estimated values	167,582	0.000008	0.43	-3.4%	-1.1521

Based on the results of our calculations, we forecast the cumulative number of BE HDTs registered in Germany from 2020 to 2060 as illustrated in Fig. 17. According to the latest registration numbers from the KBA, we have started with an initial number of 21 BE HDTs in Germany based on official data from 2019 (KBA, 2019). The S-shaped diffusion curve in Fig. 17 shows that market saturation will be reached around ten years later compared to BEVs (see Fig. 28 in the appendix). Our results reveal that there will be only 150 cumulated registrations of BE HDTs by 2025 and 961 by 2030 which equals 0.1% and 0.4% of the ultimate market potential of 168,00 HDTs. A more optimistic estimate was presented by the United States Environmental Protection Agency, assuming that 3% of HDTs will be fully electric by 2025 (Fairley, 2015). In order for an innovation to be successful, it needs to reach a critical mass for a self-sustaining diffusion (Lim, Choi and Park, 2003). According to Rogers (1983), the critical mass is defined as a minimum of 10% of the overall expected market saturation which equals 16,800 registrations of BE HDTs in Germany. Thus, the S-shaped diffusion curve in Fig. 17 shows that the critical mass will be reached by 2038. When dividing the adoption of BE HDTs into the five different adopter categories as defined in Rogers' diffusion of innovations theory, we conclude that it takes until 2034 to reach the first 2.5% of the overall market – the so-called innovators. The next 13.5%, known as the early adopters, opt for BE HDTs between 2035 and 2040 followed by the next 34%, the early majority, from

2041 to 2044. The following 34%, described as the late majority, will adopt BE HDTs from 2045 to 2048, hence, laggards which account for the last 16% of adopters will choose BE HDTs from 2049 onwards. The cumulative S-shaped curve and the bell-shaped frequency are depicted in Fig. 17 and Fig. 18.

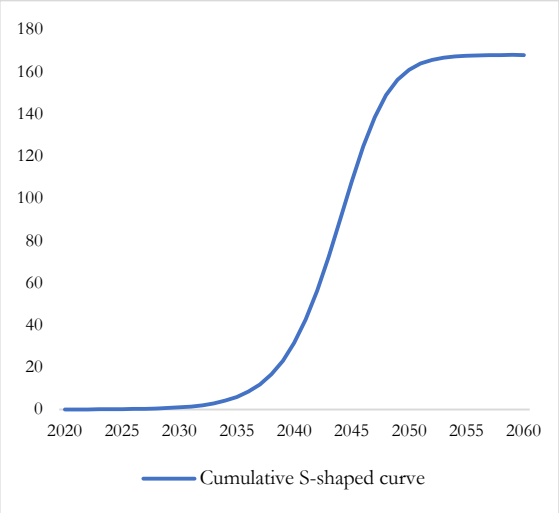

Figure 17: Cumulative S-shaped curve of BE HDTs (in thousands)

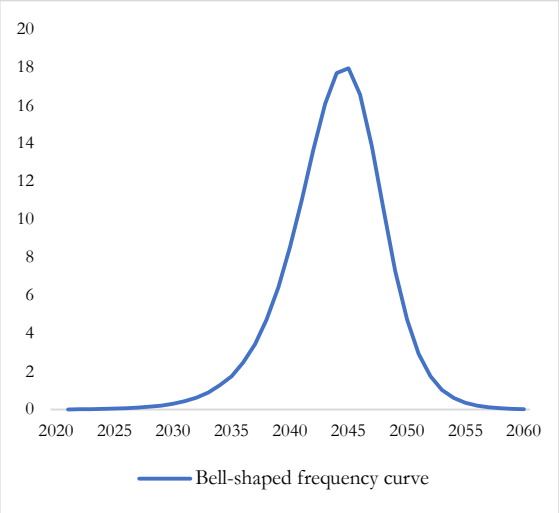

Figure 18: Bell-shaped frequency curve of BE HDTs (in thousands)

Compared to BEVs there exists only a limited number of studies focusing on alternative fuel-powered HDVs which could help to explain the comparably slow diffusion rate of analyzed BE HDTs. For instance, Kluschke *et al.* (2019) conducted a valuable literature review on the diffusion of alternative fuels and powertrains in HDVs and note that many authors even decided to exclude BE drivetrains from their analyses due to the restricted driving range. Nonetheless, other authors (e.g. Çabukoglu *et al.*, 2018; Anderhofstadt and Spinler, 2019) evaluate BE trucks as an attractive alternative for urban and short-haul transportation. MAN, one of the largest European truck manufacturers, presented its new truck generation in February 2020 and the company's CEO, Joachim Drees, noted that BE trucks will be the preferred choice for short-haul and distribution transportation by the middle of the 2020s (Handelsblatt, 2020). Anderhofstadt and Spinler (2020) conducted a choice-based conjoint experiment with employees from freight companies in Germany to present the future preference shares for autonomous and alternative fuel-powered HDTs. According to their results, only 3% of participants would choose a BE HDT over other drivetrain technologies until 2025 but preferences for BE HDTs will increase to 22% between 2030 to 2035 due to

decreasing costs and increasing efficiency. However, it is worth noting that the authors chose a purchase price which is only 40% higher compared to diesel-powered HDTs to avoid a dominance of price over other truck characteristics. Thus, current preference shares are assumingly smaller what is a possible reason for the slow ramp-up phase before reaching the early adopters and the critical mass. Moreover, the authors identified the maximum driving range as well as the refueling/recharging time as the most important attributes of alternative fuel-powered HDTs which are the major shortcomings of almost all BE vehicle categories. Nevertheless, BE drivetrains are urgently needed to reduce overall emissions and thus certain policy measures could help to drive the adoption of BE commercial vehicles in urban road freight transportation. Overall, Kluschke *et al.* (2019, p. 1019) summarize in their study that "without additional (policy) measures, the underlying market share of AFPs[5] in the HDV stock will be less than 40% and the CO_2 emission targets will not be met". Taefi *et al.* (2016) present interesting results of a multi-criteria analysis of possible policy initiatives in Germany, e.g. to financially support firms which setup charging points at their own premises. Moreover, the authors suggest to demand the use of emission-free vehicles in public tenders as well as the introduction of city tolls in order to spur the adoption rate of BE commercial vehicles in urban road freight. Moreover, as a result of their literature review, Kluschke *et al.* (2019) name R&D funding or relaxed weight regulations for alternative fuel-powered HDVs as other motivators for customers and manufacturers. Their findings are therefore in line with results presented by Anderhofstadt and Spinler (2019) who analyzed factors affecting the operation and purchasing decision of alternative fuel-powered HDTs in Germany. According to the authors, the main barriers for a widespread diffusion of BE HDTs are the high purchasing price, the lack of charging points for BE HDTs as well as the restricted driving range. In addition, a truck's reliability is essential for potential customers to avoid expensive fines due to delays. Accordingly, Mulholland *et al.* (2018) list among others the durability of batteries as well as the maximum number of charging lifecycles as current uncertainties. Overhead catenary lines for BE trucks are being tested in Germany since 2019 and are often discussed as another alternative to increase the attractiveness of electric trucks due to the possibility of recharging while driving (e.g. Çabukoglu *et al.*, 2018; Mulholland *et al.*, 2018). Moreover, according to Roger's diffusion of innovations theory, innovators and early adopters need the financial

[5] Alternative fuels and powertrains (AFP)

resources to purchase BE vehicles to set up the infrastructure and to cope with potential losses as profound information concerning reliability and durability are not available yet. Hence, the first two adopter categories, innovators and early adopters, will be most likely large firms which can then provide their experiences and feedback to the following adopter categories, the early and late majority.

4.4.1 Sensitivity analyses

Forecasting the diffusion of innovative products applying the BM is even more uncertain when it is not possible to rely on historical data from the identical product. As our parameters, and therefore also the final model, are based on the registration numbers of BEVs in Germany, we follow Park, Kim and Lee (2011) as well as Benvenutti, Ribeiro and Uriona (2017) and provide additional information in the following sections by conducting sensitivity analyses of the innovation factor p, the imitation factor q, and the external variable, the TCO decreasing rate. The necessity of performing a sensitivity analysis of results was also highlighted by Kluschke *et al.* (2019) as a conclusion from their literature review on the diffusion of alternative fuels and powertrains in HDVs.

4.4.1.1 Sensitivity analysis of innovation and imitation factor

As reliable historical data from BE HDTs in Germany do not exist, we followed Massiani and Gohs (2015) and estimated the parameters for the innovation factor p and the imitation factor q based on a similar product and the identical market: historical sales numbers of BEVs in Germany. First, we vary the innovation factor from 0.000008 to 0.0003 to test the impact on the diffusion curve. Fig. 19 shows that the originally calculated p value of 0.000008 (red-dotted line) reaches the critical mass of 10% in 2038 compared to 2035 in case of 0.0001 and 2033 when applying a value of 0.0003. Accordingly, the first 2.5% of adopters, the so-called innovators, will be reached in 2034 in case of a 0.000008 p value compared to 2029 when applying a p value of 0.0003. Hence, we conclude that changing the p value has a direct impact on when the critical mass and the first adopter categories will be reached. The influence of p is therefore most obvious when comparing the ramp-up phase from 2020 to 2035 as presented in Fig. 20. In 2025, the range of cumulated BE HDT registrations ranges from 150 (0.000008)

to 756 (0.0003) and from 961 (0.000008) to 5317 (0.0003) by 2030 depending on the applied *p* estimate. On the other hand, the impact of the innovation factor is less during the saturation phase which is also in line with findings from Park, Kim and Lee (2011, p. 3311) who describe that "after the critical mass is attained, the importance of the innovator on market penetration is reduced".

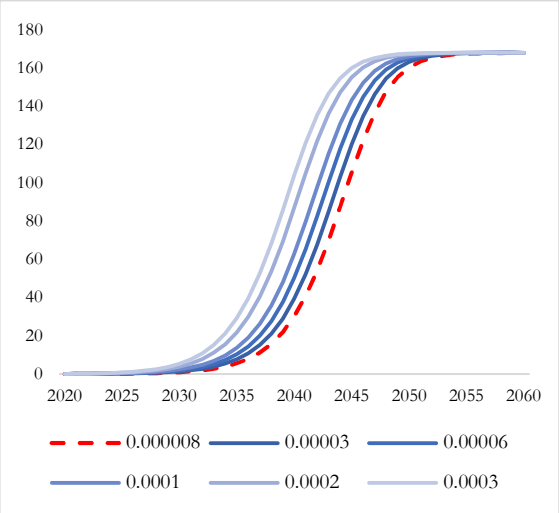

Figure 19: Sensitivity analysis of innovation factor (in thousands)

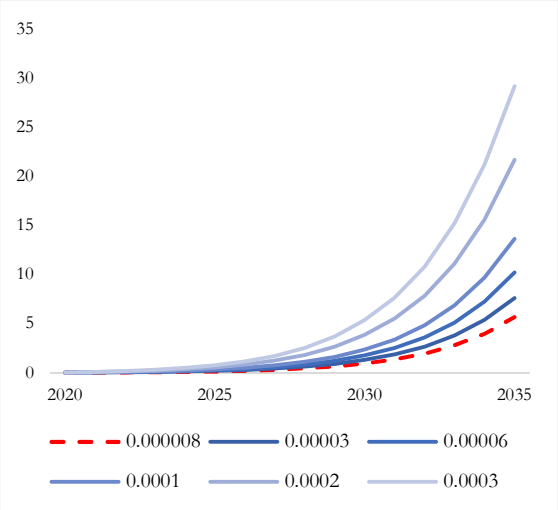

Figure 20: Sensitivity analysis of innovation factor during ramp-up phase (in thousands)

Second, the sensitivity analyses on the cumulated S-shaped curve based on changes of the imitation factor *q* reveal that the critical mass of 10% will be reached between 2036 (*q* value of 0.39) and 2039 (*q* value of 0.49) respectively. The red-dotted line shows the previously calculated *q* value of 0.43. The first 2.5% of adopters, the innovators, will be reached between 2032 and 2035. Hence, changes of the *q* value mainly affect the slope of the diffusion curve as well as the time needed to reach market saturation as displayed in Fig. 21 and Fig. 22. For instance, in case of 0.39 *q* value, laggards representing the last 16% of adopters, start purchasing the innovation by 2049 and by 2044 in case of a 0.49 *q* estimate.

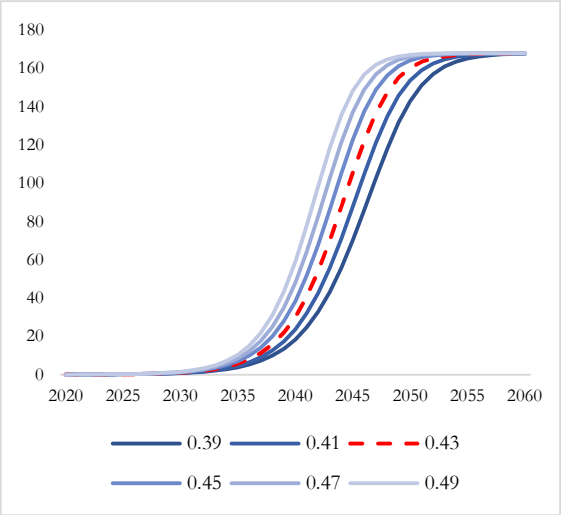

Figure 21: Sensitivity analysis of imitation factor (in thousands)

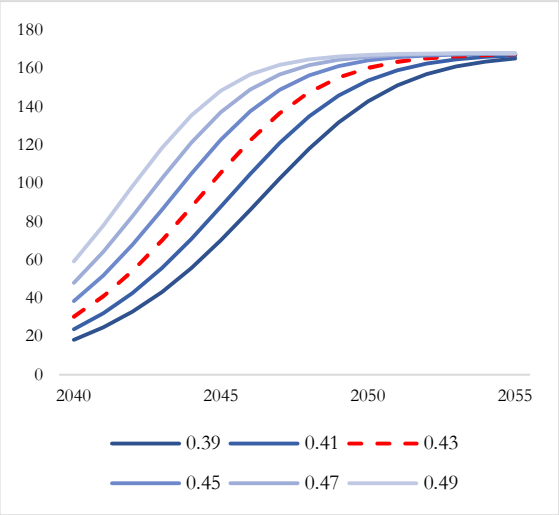

Figure 22: Sensitivity analysis of imitation factor during saturation phase (in thousands)

4.4.1.2 Sensitivity analysis of TCO reduction rate

Apart from the internal variables p and q, our final GBM was also influenced by an external variable. According to previous studies, we chose the TCO as an important factor affecting the diffusion of BE HDTs in Germany. Based on our calculations in section 3.2.3, we assume that the TCO reduction rate of BE HDTs will be 3.4% (red dotted line) annually compared to diesel-powered HDTs. Hence, under this assumption TCO parity will be reached by 2027 and the previously defined maximum TCO benefit of 20% between BE and diesel HDTs by 2034, i.e. costs are not decreasing from 2034 onwards and the 20% cost gap remains stable. In order to display potential changes such as the inclusion or exclusion of certain financial subsidies, we vary the reduction rate from 0.1% to 7.5% annually. For instance, in case of an annual 7.5% TCO reduction rate, the pre-defined 20% TCO benefit relative to diesel-powered HDTs will be reached by 2027. On the other hand, a decrease of 1% leads to TCO parity by 2045 and the defined maximum TCO gap of 20% by 2067. Despite the importance of the TCO, especially in case of commercial vehicles, Fig. 23 displays that there is only a slight difference in the S-shaped diffusion curve when varying the TCO reduction rate. As stated previously, we followed Benvenutti, Ribeiro and Uriona (2017) and utilized a β_1 of -1.1521 based on Park, Kim and Lee (2011). However, when choosing a higher value for β_1, the TCO reduction rate would have a higher impact on the adoption rate of BE HDT. Fig. 24 shows the impact on the ramp-up phase from 2020 to 2035. We conclude that especially a reduction

rate of 3.4%, 5% and 7.5% results in very similar adoption rates as those three values reach cost parity and the defined 20% TCO gap relatively soon. Nevertheless, Fig. 24 displays that there will be around 5,000 cumulated BE HDT registrations by 2035 in case of a 0.1% reduction rate and more than 6,000 vehicles when assuming a 7.5% TCO reduction per annum. Thus, in accordance with economic theory, a higher TCO decreasing rate leads also to higher adoption rates.

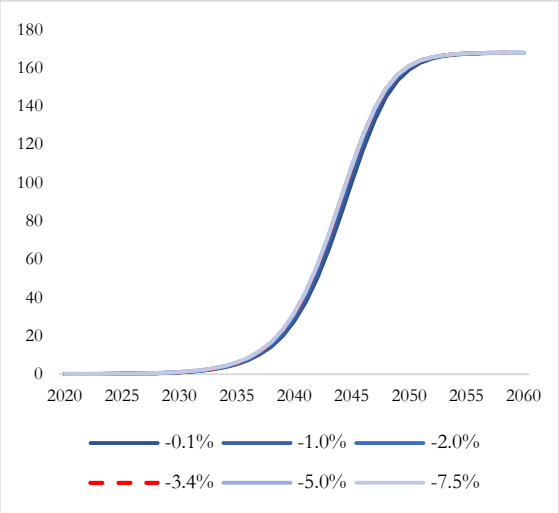

Figure 23: Sensitivity analysis of TCO reduction rate (in thousands)

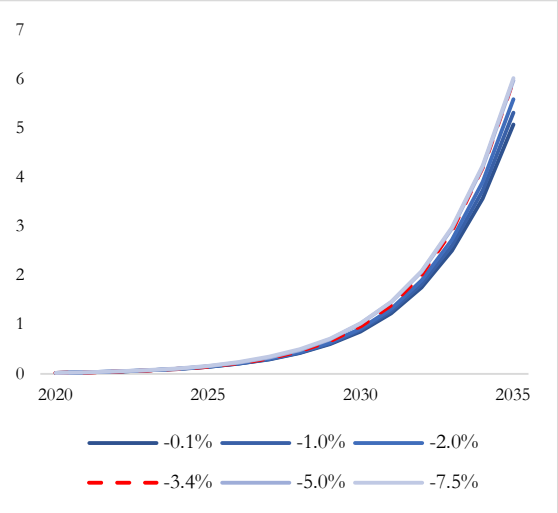

Figure 24: Sensitivity analysis of TCO reduction rate during ramp-up phase (in thousands)

4.5 Conclusion

This study aimed to forecast the future diffusion of BE HDTs in Germany considering TCO reduction effects by applying the GBM which is a modified version of the widely used BM. Compared to the traditional BM, the GBM includes external variables which affect the diffusion of innovative products. First, we defined the market potential m for BE HDTs in Germany based on the average mileage driven per HDT in Germany. Second, we estimated the innovation factor p and the imitation factor q by utilizing historical monthly data of BEV registrations in Germany from 2010 to 2019. Third, we followed previous studies on alternative fuel-powered commercial vehicles and calculated the future TCO of BE and diesel-powered HDTs. The average TCO reduction rate of 3.4% annually between both technologies was included as the external variable since the TCO is considered a vital factor for fleet managers when purchasing commercial vehicles (Sierzchula, 2014). In addition, we conducted

sensitivity analyses for the innovation factor, the imitation factor and the TCO reduction rate to display the effects of potential changes on the diffusion rate. Our findings are therefore of great importance for policymakers, truck manufacturers but also for the strategy formulation of truck customers that aim for a sustainable supply chain.

By implementing the estimated parameters into the GBM, we could show that it takes until 2038 to reach the critical mass of 10% of the overall potential market which is essential in order to realize a self-sustaining diffusion process of an innovation. Despite the practical importance of our model, the diffusion of innovations theory by Rogers (1983) including the different adopter categories played a key role in guiding the execution of our study. Even though BE HDTs from truck manufacturers are available on the market, only 21 BE HDTs were registered in Germany as of January 2019. Accordingly, our results reveal a long ramp-up phase and innovators, representing the first 2.5% of potential adopters, will be reached by 2034 only. The presented S-shaped diffusion curve in Fig. 17 shows that the period from 2040 to 2050 will be the phase with the highest number of adoptions due to the early and late majority followed by the saturation phase where also laggards, the last 16% of potential adopters, opt for BE HDTs. The performed sensitivity analysis was used to show the impact of the different parameters on the diffusion process. We conclude that the innovation factor mostly affects the ramp-up phase whereas the imitation factor has an impact on the slope of the diffusion curve and the time needed to reach market saturation. On the other hand, our results illustrate that a varying TCO reduction rate from 0.1% to 7.5% has a comparably low effect on the diffusion rate of BE HDTs. This is due to the defined maximum TCO difference of 20% between diesel and BE HDTs and, on the other hand, because of the chosen β_1 based on Park, Kim and Lee (2011) which affects the impact on the adoption rate as well. All in all, our diffusion forecasting model shows that freight companies will not switch from diesel-powered to BE HDTs over night and it is therefore essential to underline relevant recommendations which can help to spur the number of BE HDTs in Germany. Rogers (1983) describes that existing uncertainties need to be reduced to increase the number of innovations in the system, however, similar to the introduction of BEVs, only little information concerning costs, reliability or battery lifetime of BE HDTs is available. Hence, Schulte, Hart and Van der Vorst (2004) recommend test drives and hands-on experience to reduce skepticism toward new technologies which will then help to convince especially

innovators and early adopters to switching from diesel to BE HDTs. According to Rennings *et al.* (2006), environmental policy instruments as well as financial subsidies from innovation policy could additionally help to increase the adoption of eco-innovations such as electric vehicles. Thus, we recommend to extending current subsidies such as the purchase subsidy of 40,000 Euros for all-electric HDTs and the exemption from road tolls. Another possible incentive could be to overturn the current holiday and Sunday ban for all trucks when operating a fully electric vehicle. Moreover, legal restrictions such as diesel-bans in city centers can additionally motivate freight companies to substitute conventional HDTs by BE vehicles, especially in case of city distribution as well as shuttle- and short-haul transportation (Anderhofstadt and Spinler, 2019). Companies operating BE commercial vehicles usually perform private charging, however, public charging points are evaluated as a supportive aspect. The ACEA (2019) criticizes in their report about alternative fuel-powered trucks that public high power-charging points for BE trucks of more than 500 kW would be necessary to reach the set emission reduction targets but there was not even a European standard for plugs defined yet. Nevertheless, Daimler (2020) started its "eTruck Charging Initiative" in cooperation with other companies to support their customers during the transformation toward electric road transportation and to set up the necessary charging infrastructure, both publicly available and at the depot of truck customers. As this is subject to costly investments, we recommend financial subsidies for companies when installing private charging stations for BE commercial vehicles. Moreover, we follow Quak, Nesterova and van Rooijen (2016) and recommend investments in the training of truck drivers to improve eco-friendly driving and the ability to promote the benefits of BE HDTs to their customers. This is in line with findings from Baster *et al.* (2014) who describe that a company's green image should be perceived as a future investment which is not immediately profitable but helps to strengthen existing customer relationships and to attract new businesses.

Our model provides interesting results on the anticipated diffusion of BE HDTs in Germany considering TCO reduction effects, however, certain limitations of the study need to be addressed. First, we used historical data of BEVs in Germany to calculate the innovation and imitation factor but the adoption process of BE commercial vehicles could follow a different path. We therefore recommend to consider registration numbers of BE light-duty trucks in future research which may become available rather soon. Second, the estimated market

potential could be affected by the introduction of FCE HDTs since the technology benefits from locally emission-free transportation, short refueling times and a higher driving range. However, reliable data about technical specifications and costs are not available yet. Third, the expected purchase price of BE HDTs in the conducted TCO analysis is three times higher than that of diesel-powered HDTs but the final purchase price of BE HDTs heavily depends on the needed battery size based on the transportation process. Future TCO analyses would therefore benefit from observing various battery packs for different transportation scenarios. Lastly, we followed previous studies and assume private charging at the depot in our TCO calculation and therefore decided to exclude those costs from our analysis. Similar to different battery capacities, infrastructure costs could be incorporated in future TCO calculations as soon as reliable information becomes available. Other directions for future research are the extension to different countries due to varying boundary conditions concerning electric vehicles, e.g. legal restrictions or financial subsidies. Moreover, we recommend to analyze the impact of BE HDTs on the German electricity generation as previous studies agree that the transportation sector will become a key participant, especially with respect to renewable energy (Kluschke *et al.*, 2019).

5. Summary and conclusion

There is a bumpy road ahead for the trucking industry due to strict environmental targets, new competition and several megatrends which will transform the industry drastically. Germany is not only one of the largest emitters of greenhouse gas emissions worldwide, but also a leading manufacturer of HDTs. This dissertation aims to contribute to the understanding of a successful transition toward autonomous and alternative fuel-powered HDTs in Germany and is of great importance to both practitioners and academics. The previous chapters showed that there will not be *one* type of alternative fuel or drivetrain which will replace diesel-powered HDTs in the short-term. For instance, BE vehicles are a market-ready technology and well suited for locally emission-free city distribution and short-haul shuttle transportation whereas liquefied natural gas is a market-ready substitute for long-haul operations which can help to reduce air pollution. However, environmental benefits of natural gas trucks are limited and will not help to reach a carbon-neutral society, hence, the long-term future of trucking must be fully electric to reduce harmful emissions from road freight transportation. Fuel cell electric trucks will therefore play a key role as they combine the main benefits of BE and natural gas drivetrains: (i) locally emission-free transportation, (ii) a reasonable driving range, and (iii) short refueling times. However, fuel cell electric trucks are not yet commercially available but are currently being developed by several manufacturers such as Hyundai or IVECO/Nikola. Furthermore, it is important to note that well-to-wheel analyses must be the standard process for a comprehensive assessment of emissions from road transportation. Hence, electricity generation from renewable sources will be key in order to realize emission-free transportation. Accordingly, the transportation sector will become a main recipient of German electricity generation due to the production of hydrogen and recharging of BE vehicles. Apart from environmentally friendly powertrains, self-driving technology will play a key role in the future of trucking due to a severe shortage of qualified drivers. According to recent research from the International Road Transport Union (IRU), the European logistics sector is facing an increased shortage of qualified drivers in 2020, rising from 23% in 2019 to 36% in 2020 (IRU, 2020).

The second chapter laid the foundation of this dissertation by conducting a Delphi study on factors affecting the purchasing decision and operation of alternative fuel-powered HDTs in Germany. The final Delphi panel consisted of a heterogenous expert group with participants

from truck manufacturers, logistics service providers, infrastructure companies, consulting firms, and research institutions. The execution of the Delphi study was guided by theories on the adoption process of eco-innovations. The main body of the chapter was divided into Part A and Part B. Part A focused on 34 relevant factors collected from various scientific studies which were tested with respect to stability and consensus of the experts' replies as well as their relative importance. The results revealed that a truck's reliability, the availability of fueling/charging stations, and the possibility to enter low-emission zones are the three most important aspects when purchasing and operating alternative fuel-powered HDTs in Germany. Based on a pre-defined threshold for the interquartile range of 1.0 and the change in the coefficient of variation of 0.1, the three factors reached stability and consensus among the Delphi experts. Part B, on the other hand, discussed motivators, barriers, and possibilities to overcome the main barriers when switching from conventional diesel-powered drivetrains to promising substitutes which were defined in cooperation with an expert group: battery electric, hydrogen fuel cell, compressed natural gas, and liquefied natural gas. Among others, experts criticized the number of available refueling/recharging stations across Germany for the different technologies which was also assessed as one of the most critical factors in Part A. The panel recommended environmental restrictions such as low-emission zones as a promising possibility to spur the number of low-emission vehicles in Germany.

In chapter three, the focus was shifted to customers of HDTs, i.e. freight companies. The results of an online choice-based conjoint experiment were presented which was designed with Sawtooth software, a standard tool in academia for designing and evaluating conjoint studies. Theories on the acceptance and use of new technologies served as helpful guidance for the execution of the conjoint experiment. A list of relevant attributes and levels of innovative HDTs was derived based on the technical specifications of existing alternative fuel-powered HDTs, expert interviews, and extensive desk research. In order to design an effective choice task, the following six attributes were defined and presented to the participants of the experiment: the level of driving automation, the maximum driving range with a full tank/battery, the refueling/recharging time, the lifetime operating costs, the purchase price, and tank-to-wheel emissions. The relative average importances of the conducted experiment showed that operational attributes such as a high driving range and a short refueling time are most important to truck customers followed by cost factors. Furthermore, results reveal that

freight companies value the benefits of self-driving technology as well but were indifferent between partial and full automation. Tank-to-wheel emissions were ranked as the least relevant attribute. Furthermore, battery electric, hydrogen fuel cell, compressed natural gas, and liquefied natural gas were chosen as relevant drivetrains in the future and different scenarios were defined until 2035 to see how preference shares of customers will change over time. The results show that customers prefer liquefied natural gas and conventional diesel-powered trucks in the first timeframe from 2020 to 2025 but preference shares of fully electric trucks, i.e. equipped with BE and FCE drivetrain, increase over time and will be the preferred solutions from 2030 to 2035.

In the fourth chapter, we[6] built on the findings of the previous chapter which showed the increasing attractiveness of fully electric drivetrains and applied the Generalized Bass Diffusion model to forecast the market penetration of BE HDTs in Germany. As the Bass model builds on Rogers' diffusion of innovations theory, it was chosen as the guiding theory of the research process. First, the market potential of BE HDTs was estimated based on the average mileage driven per day in Germany. Second, we utilized historical monthly registration numbers of BEVs from 2010 to 2019 to estimate the innovation and imitation factor. Third, we gathered information concerning the main cost parameters of diesel and BE HDTs to calculate the total-cost-of-ownership reduction effects in Germany which we have incorporated as an external variable into our model. Due to high initial one-time investments, BE HDTs are currently more expensive than their diesel-powered counterparts but our analysis showed that the total-cost-of-ownership will decrease by around 3.4% annually leading to cost parity between diesel and BE powertrains by 2027. Nevertheless, based on the estimated Bass parameters, the critical mass of 10% of the overall market potential will be achieved by 2038 only but is essential to realize a self-sustaining diffusion process. Lastly, sensitivity analyses of the estimated parameters were conducted.

In conclusion, the trucking industry is at the beginning of a new era which is accompanied by uncertainties and skepticism. Support from environmental and innovation policy is necessary to accelerate research and development in low-emission drivetrains and the setup of charging/fueling stations across the country but also to motivate truck customers to switching

[6] The term „we" refers to the authors of the respective studies as denoted at the beginning of each chapter.

from conventional to innovative HDTs. Thus, a close collaboration between truck manufacturers, customers, policymakers, and infrastructure companies, aligned with European strategies, is required to transform the industry and to realize a successful market penetration of autonomous and alternative fuel-powered HDTs in Germany.

Appendix

Appendix to Chapter 2

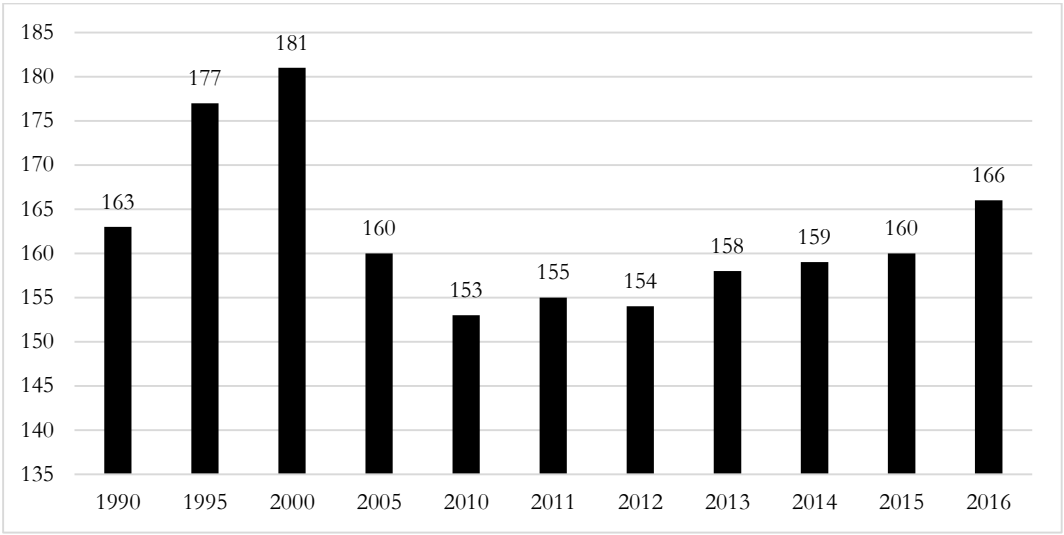

Figure 25: Greenhouse gas emissions from transport in Germany in million tons from 1990-2016 (based on BMU, 2017a)

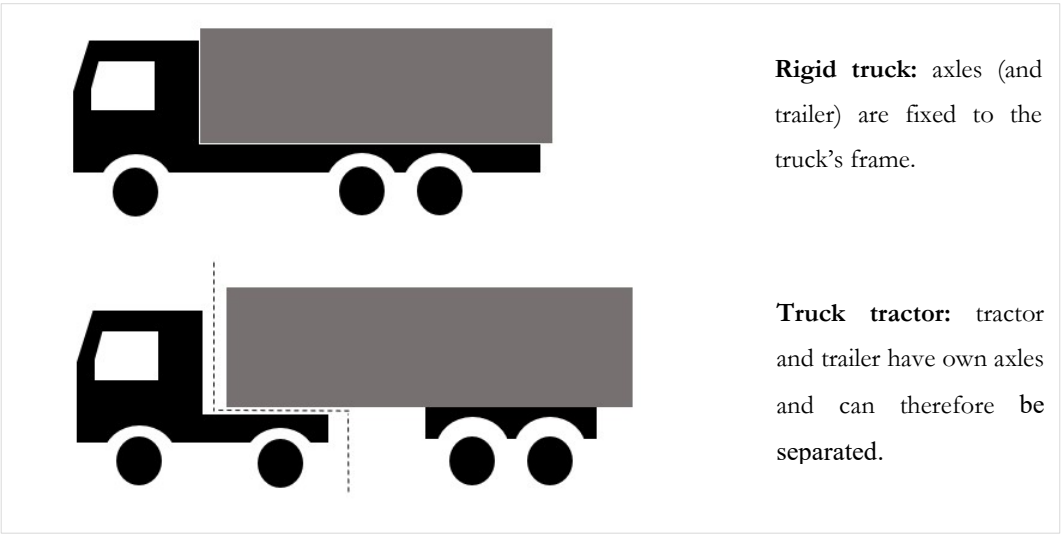

Figure 26: Rigid truck and truck tractor unit

Table 12: Factors affecting the purchasing decision and operation of alternative fuel-powered HDTs in Germany

Factors	Category	Sources
1. Current fuel costs	Costs	(Ozaki and Sevastyanova, 2011)
2. Future trend in fuel costs	Costs	(Davis and Figliozzi, 2013)
3. Service and maintenance costs	Costs	(Davis and Figliozzi, 2013)
4. Expenses for repairs	Costs	(Hagman *et al.*, 2016)
5. Purchasing price	Costs	(Davis and Figliozzi, 2013)
6. Taxes and insurance	Costs	(Ozaki and Sevastyanova, 2011)
7. Depreciation/Resale value	Costs	(Davis and Figliozzi, 2013)
8. Being a trendsetter in environmental-friendly technologies	Socioeconomic factors	(Ozaki and Sevastyanova, 2011)
9. Being part of socially responsible activities (marketing/reputation)	Socioeconomic factors	(Ozaki and Sevastyanova, 2011)
10. General excitement about new technologies/innovations	Socioeconomic factors	(Ozaki and Sevastyanova, 2011)
11. Greenhouse gas emission	Environmental factors	(Knez, Jereb and Obrecht, 2014)
12. Noise emission	Environmental factors	(Knez, Jereb and Obrecht, 2014)
13. Ecological impact of truck manufacturing and recycling	Environmental factors	(Onat *et al.*, 2016)
14. Well-to-Tank emissions	Environmental factors	(Alamia *et al.*, 2016)
15. Tank-to-Wheel emissions	Environmental factors	(Alamia *et al.*, 2016)
16. Well-to-Wheel emissions	Environmental factors	(Alamia *et al.*, 2016)
17. Reliability	Daily practicability	(Ozaki and Sevastyanova, 2011)
18. Refueling time	Daily practicability	(Junquera, Moreno and Álvarez, 2016)
19. Maximum vehicle driving range	Daily practicability	(Davis and Figliozzi, 2013)
20. Safety features	Daily practicability	(Knez, Jereb and Obrecht, 2014)
21. Maximum payload capacity	Daily practicability	(Davis and Figliozzi, 2013)
22. Brand/model of vehicle	Daily practicability	(Knez, Jereb and Obrecht, 2014)
23. Service quality of manufacturer	Daily practicability	(Kiani, 2017)
24. Fueling/charging infrastructure	Daily practicability	(Sierzchula *et al.*, 2014)
25. Manufacturers' warranties	Daily practicability	(Knez, Jereb and Obrecht, 2014)
26. Vehicle design	Daily practicability	(Ozaki and Sevastyanova, 2011)
27. Driver comfort	Daily practicability	(Ozaki and Sevastyanova, 2011)
28. Performance/driveability	Daily practicability	(Ozaki and Sevastyanova, 2011)
29. Level of extra equipment	Daily practicability	(Tzeng, Lin and Opricovic, 2005)
30. Fuel specifications in tenders	Political factors	(Taefi *et al.*, 2016)
31. Possibility to enter low-emission zones	Political factors	(Taefi *et al.*, 2016)

32. Possibility to enter low-noise zones	Political factors	(Taefi *et al.*, 2016)
33. Financial incentives when purchasing/operating an alternative fuel-powered truck	Political factors	(Taefi *et al.*, 2016)
34. Independence of oil producers	Political factors	(Yeh, 2007)

Appendix to Chapter 3

Table 13: Optimistic scenario 1) 2020-2025, 2) 2025-2030, 3) 2030-2035

Technology	Automated driving	Driving range	Refueling time	Operating costs	Purchase price	TtW emissions	Shares of preference
BE[1)]	Level 0-2	200 km	4 h 30 min	-20 %	40 %	-100 %	4.1 %
CNG[1)]	Level 0-2	400 km	10 min	0 %	0 %	-25 %	4.2 %
LNG[1)]	Level 0-2	1600 km	10 min	0 %	0 %	-25 %	70.0 %
None[1)]							21.6 %
BE[2)]	Level 3-4	400 km	1 h 30 min	-40 %	0 %	-100 %	16.8 %
CNG[2)]	Level 3-4	400 km	10 min	-20 %	0 %	-25 %	2.7 %
LNG[2)]	Level 3-4	1600 km	10 min	-20 %	0 %	-25 %	55.5 %
FCE[2)]	Level 3-4	800 km	10 min	-20 %	40 %	-100 %	19.4 %
None[2)]							5.6 %
BE[3)]	Level 5	800 km	30 min	-40 %	-20 %	-100 %	32.3 %
CNG[3)]	Level 5	400 km	10 min	-40 %	0 %	-25 %	2.2 %
LNG[3)]	Level 5	1600 km	10 min	-40 %	0 %	-25 %	17.6 %
FCE[3)]	Level 5	1600 km	10 min	-40 %	0 %	-100 %	43.0 %
None[3)]							5.1 %

Table 14: Pessimistic scenario 1) 2020-2025, 2) 2025-2030, 3) 2030-2035

Technology	Automated driving	Driving range	Refueling time	Operating costs	Purchase price	TtW emissions	Shares of preference
BE[1)]	Level 0-2	200 km	4 h 30 min	20 %	40 %	-100 %	2.4%
CNG[1)]	Level 0-2	400 km	10 min	20 %	20 %	-25 %	2.8%
LNG[1)]	Level 0-2	1600 km	10 min	20 %	20 %	-25 %	24.0%
None[1)]							70.9%
BE[2)]	Level 0-2	400 km	1 h 30 min	0 %	20 %	-100 %	21.8%
CNG[2)]	Level 0-2	400 km	10 min	20 %	20 %	-25 %	1.1%
LNG[2)]	Level 0-2	1600 km	10 min	20 %	20 %	-25 %	14.5%
FCE[2)]	Level 0-2	400 km	10 min	20 %	40 %	-100 %	3.2%
None[2)]							59.4%
BE[3)]	Level 3-4	400 km	1 h 30 min	-20 %	40 %	-100 %	8.1%
CNG[3)]	Level 3-4	400 km	10 min	0 %	40 %	-25 %	1.4%
LNG[3)]	Level 3-4	1600 km	10 min	0 %	40 %	-25 %	20.4%
FCE[3)]	Level 3-4	800 km	10 min	0 %	40 %	-100 %	41.8%
None[3)]							28.3%

Appendix to Chapter 4

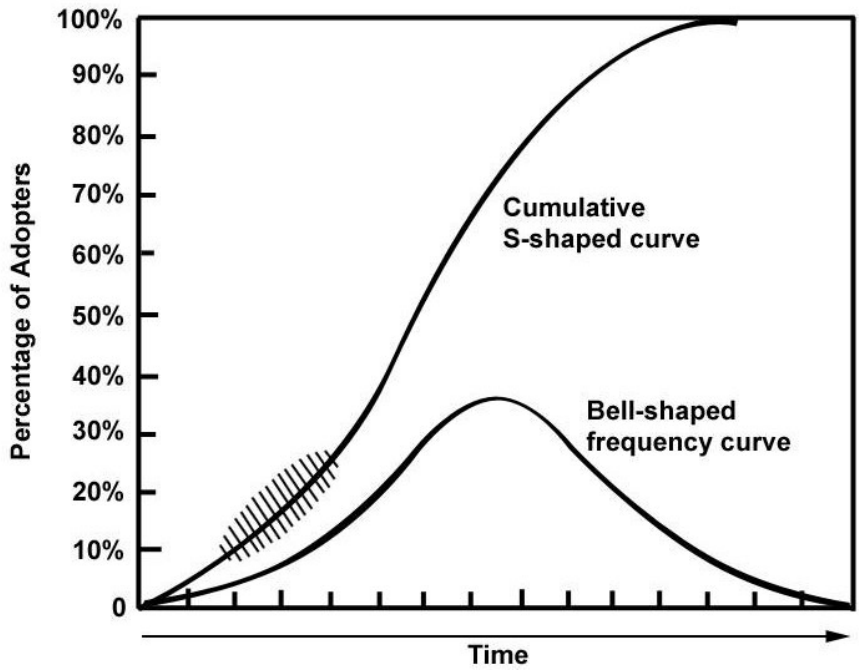

Figure 27: Cumulative S-shaped curve and bell-shaped frequency curve from Rogers (1983, p. 243)

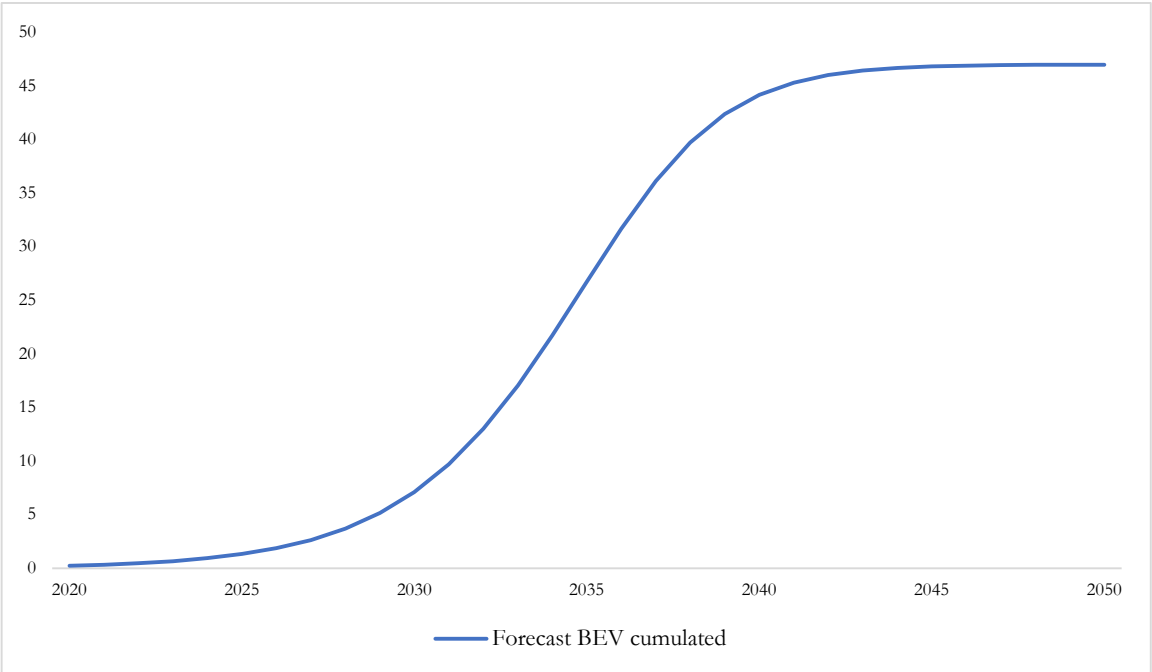

Figure 28: Forecast cumulative number of BEVs in Germany from 2020 to 2050 (in millions)

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