

# **Adoption and Diffusion of Electric Trucks in Urban Freight Transport**

Von der Fakultät Wirtschafts- und Sozialwissenschaften  
der Universität Stuttgart zur Erlangung der Würde eines  
Doktors der Wirtschafts- und Sozialwissenschaften (Dr. rer. pol.)  
genehmigte Abhandlung

Vorgelegt

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Tag der mündlichen Prüfung: 25.04.2019

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2019

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## LIST OF ABBREVIATIONS

ACEA	European Automobile Manufacturers' Association
BCP	Battery Charging Point
BEV	Battery Electric Vehicle
CCZ	Congestion Charge Zone
CI	Carbon Intensity
CNG	Compressed Natural Gas
CO <sub>2</sub>	Carbon dioxide
CO <sub>2</sub> e	Carbon dioxide equivalent
DfT	Department for Transport
Dmnl	Dimensionless
ECE-R101	Regulation No 101 of the Economic Commission for Europe
E.G.	Exempli Gratia
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GVW	Gross Vehicle Weight
H <sub>2</sub>	Hydrogen
HDV	Heavy-Duty Vehicle
HGV	Heavy Goods Vehicle
HRS	Hydrogen Refuelling Station
ICCT	International Council on Clean Transportation

ICEV	Internal Combustion Engine Vehicle
IIA	Independence from Irrelevant Alternatives Property
LEZ	Low Emission Zone
LGV	Light Goods Vehicles
MDV	Medium-Duty Vehicle
MY	Model Year
NH <sub>3</sub>	Ammonia
NHTSA	National Highway Traffic Safety Administration
NMHC	Non-Methane Hydrocarbons
NMVOCs	Non-Methane Volatile Organic Compounds
NO <sub>x</sub>	Nitrogen oxide
OEM	Original Equipment Manufacturer
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Matter
R&D	Research and Development
REEV	Range Extended Electric Vehicle
ROS	Return on Sales
SCR	Selective Catalytic Reduction
SO <sub>2</sub>	Sulphur Dioxide
TCO	Total Cost of Ownership
TfL	Transport for London
TTW	Tank-to-Wheel
UK	United Kingdom (England, Wales, Scotland, Northern Ireland)
ULEV	Ultra Low Emission Vehicle
ULEZ	Ultra Low Emission Zone

VECTO	Vehicle Energy Consumption Calculation Tool
V2G	Vehicle to Grid
WtC	Willingness to Consider
WTT	Well-to-Tank
WTW	Well-to-Wheel
ZEV	Zero Emission Vehicle
ZEZ	Zero Emission Zone

## LIST OF UNITS OF MEASUREMENT

£	British Pound
€	Euro
\$	US Dollar
%	Percent
g	Gramm
h	Hour
kg	Kilogram
km	Kilometre
kW	Kilowatt
kWh	Kilowatt Hour
l	Litre
M	Million
m <sup>3</sup>	Cubic Metre
min	Minute
MJ	Megajoule
t	Tonnes
Wh	Watthour

## **ACKNOWLEDGEMENT**

First of all, I want to express my deepest gratitude to Professor Englmann for his interest in the topic and the opportunity to pursue a dissertation as an external doctorate student in parallel to my job at Daimler AG. This thesis would not have been possible without his critical remarks and help. Furthermore, I wish to acknowledge the contribution of Professor Woeckener and all the doctorate students of the Institute for Economics and Law during the seminars at the University of Stuttgart. I am also very grateful for the fruitful discussions that I had with Dr. Marion Aschmann from the University of Stuttgart.

Finally, I want to thank my family for their endless love and support.

## **ABSTRACT**

The year 2018 could be seen as a major milestone in the transition of the trucking industry to electrification. The European Union finally announced the introduction of a CO<sub>2</sub> emission standard and a zero emission vehicle sales mandate for the years 2025 and 2030. By this, the European Union wants to catch up with other markets like the United States, which already has CO<sub>2</sub> emission standards and sales mandates in place. Established truck manufacturers are not only pressured by regulatory measures but are also threatened by new market players like Tesla or Thor Trucks. They reacted with a firework of new electric trucks at the 2018 International Motor Show in Germany. Electric vehicles in urban road freight transport are not new as transport companies were already deploying them at the start of the 20<sup>th</sup> century. However, the pace with which the battery technology is improving and the battery cost is falling gives hope that the electric drivetrain has finally overcome its teething troubles. Is the transportation renaissance in freight transport in the form of electric trucks here to stay and how many years will it take until the incumbent diesel engine is dethroned? Despite overall confidence in the electric drivetrain, there is no denying the fact that the truck customer has the final say. Deriving market share forecasts purely from technological advances and assuming that customers have complete information and based on this behave in an economically rational way has produced overoptimistic results for electric vehicles. To improve the market share forecast accuracy, this integrated the rational inattention theory into a System Dynamics Model that can be used as a forecasting tool. This model has been used to forecast the market diffusion of electric trucks in urban transport in the United Kingdom until 2050. To understand the influence of different technical, political and economic model parameters on the market diffusion of electric trucks, different scenarios have been simulated. The simulation results show that electric trucks will gain a considerable market share until 2050 but will not be able to fully displace diesel trucks.

## KURZFASSUNG

Das Jahr 2018 könnte als wesentlicher Meilenstein im Übergang des Güterkraftverkehrsgewerbes zur Elektrifizierung betrachtet werden. Die Europäische Union hat schließlich die Einführung von CO<sub>2</sub>-Grenzwerten und eine Verkaufsquote für emissionsfreie Lastkraftwagen für die Jahre 2025 und 2030 angekündigt. Dadurch möchte die Europäische Union zu anderen Märkten wie die Vereinigten Staaten aufschließen, die bereits CO<sub>2</sub>-Grenzwerte und eine Verkaufsquote haben. Auf die etablierten Lastkraftwagenhersteller wird nicht nur durch regulatorische Maßnahmen Druck ausgeübt, sondern sie werden auch durch neue Marktakteure wie Tesla oder Thor Trucks bedroht. Sie reagierten darauf mit einem Feuerwerk an neuen Elektronutzfahrzeugen auf der Internationalen Automobilausstellung Nutzfahrzeuge 2018 in Deutschland. Elektrofahrzeuge sind keine Neuigkeit im urbanen Lieferverkehr, da sie bereits zu Beginn des 20. Jahrhunderts durch Transportunternehmen eingesetzt wurden. Die Geschwindigkeit mit der die Batterietechnologie voranschreitet und die Batteriekosten fallen gibt jedoch Anlass zur Hoffnung, dass der Elektroantrieb letztlich seine Kinderkrankheiten überwunden hat. Ist die Renaissance im Transportwesen gekommen um zu bleiben und wie viele Jahre wird es dauern bis der vorherrschende Dieselantrieb entthront wird? Trotz allem Vertrauen in den Elektroantrieb lässt sich nicht leugnen, dass der Lastkraftwagenkunde das letzte Wort hat. Marktanteilsprognosen allein anhand des technischen Fortschritts abzuleiten und anzunehmen, dass Kunden vollständige Informationen haben und darauf aufbauend sich ökonomisch rational verhalten hat zu überoptimistischen Ergebnissen für Elektrofahrzeuge geführt. Um die Genauigkeit von Marktanteilsprognosen zu verbessern, wurde die Theorie der Rationalen Unaufmerksamkeit in ein System Dynamics Modell integriert, das als Prognosewerkzeug eingesetzt werden kann. Dieses Modell wurde genutzt, um die Marktdiffusion von Elektronutzfahrzeugen im urbanen Lieferverkehr im Vereinigten Königreich bis 2050 zu schätzen. Um den Einfluss von verschiedenen technischen, politischen und ökonomischen Modellparametern auf die Marktdiffusion von Elektronutzfahrzeugen zu verstehen, wurden verschiedene Szenarien simuliert. Die Simulationsergebnisse zeigen, dass Elektronutzfahrzeuge bis 2050 einen

erheblichen Marktanteil erreichen werden aber das Dieselnutzfahrzeug nicht vollständig verdrängen können.

# 1. INTRODUCTION

## 1.1 REVOLUTION IN URBAN ROAD FREIGHT TRANSPORT

Electric drivetrains are increasingly gaining attention in urban freight transport, as they are praised as the ideal solution for the urging environmental problems of cities. What many people do not know: a century ago, electric vehicle supporters in the trucking industry believed “that the electric vehicle is destined to supersede other forms of transportation methods at least for city and suburban work.”<sup>1</sup> Indeed up to mid-1920s, the number of electric trucks used in urban freight operations ranged into thousands.<sup>2</sup> The electric motor was used in nearly 40 percent of all trucks in New York in 1914 for vehicle propulsion.<sup>3</sup> What persuaded the customers to buy and use the electric truck then and why did it fell into oblivion for such a long time? And what basis do we have for believing that the electric truck will reemerge triumphantly like Phoenix from the ashes? Before the invention of the motor vehicle, the only way to transport freight in cities was by horse carriages<sup>4</sup>. Fleet operators quickly recognized that the motor truck had many benefits. One of the outstanding advantages was the possibility to serve more customers and customers that are located further away, which was achieved because the transportation with motor vehicles was faster and more flexible.<sup>5</sup> However, the transition from horse-drawn freight transport to motor-driven freight transport didn’t happen overnight, because “businesses had developed a host of practices adapted to the capabilities of the horse.”<sup>6</sup> There was a transitional period until 1930 during which horse-drawn vehicles, electric trucks and gasoline trucks fought for predominance in freight transport. The electric truck quickly found a market niche, as the fleet operator was able to keep his operational routines working. One example is the short break in which the horses could rest and drink water, while the driver sampled the product with the buyer<sup>7</sup>. This short break could be used to charge the batteries. The electric vehicle did not only offer a higher range than a horse-drawn vehicle but also had lower running costs than a gasoline truck when

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<sup>1</sup> Mom, G. and Kirsch, D. (2001), p. 513

<sup>2</sup> Ibid., p. 490

<sup>3</sup> Ibid., p. 506

<sup>4</sup> Nakicenovic, N. (1986), p. 313

<sup>5</sup> Ibid. 316

<sup>6</sup> Mom, G. and Kirsch, D. (2001), p. 499

<sup>7</sup> Ibid.,

certain conditions were given.<sup>8</sup> The technical and financial advantages of electric trucks in certain fields of operation led to the belief that the coexistence of multiple technologies will remain:

Experience will furnish the decisive evidence which shall assign each motive power to its appropriate sphere. Light delivery work in congested areas will perhaps become the province of the electric vehicle. In sparsely settled territory this duty may devolve upon the gasoline engine, while steam may do the bulk of the heavy trucking, pending the application of internal combustion engines to this service.<sup>9</sup>

However, history has shown that the electric truck was not capable of becoming the dominant technology for urban delivery services for several reasons. A major factor behind the failure of the battery electric truck was that small businesses, which represented around 90 percent of the freight market, did not purchase them.<sup>10</sup> Although electric truck maintenance and operating costs were lower than for gasoline engine trucks, small businesses were not able to burden the high upfront investment costs of electric trucks.<sup>11</sup> Electric truck supporters tried to increase the attractiveness of the electric truck by making them cheaper to buy.<sup>12</sup> The first battery-swapping service was introduced by Hartford Electric Light Company and was called Battery Service System (BSS), which offered trucks without batteries to businesses, but with the possibility to swap the battery in a BSS garage as often as necessary when it was discharged<sup>13</sup>. Depending on the size of the truck and monthly mileage, the vehicle owner received a bill by the end of the month.<sup>14</sup> Despite these remarkable efforts, the gasoline engine truck prevailed thanks to its versatility, which became obvious during World War I in Europe.<sup>15</sup> The war set standards for commercial vehicles regarding “speed, range and other performance measures”, which the electric truck was not able to meet.<sup>16</sup> Thus, the war standards acted as a catalyst for gasoline engine trucks and the economies of scale achieved during the years of war led to increasing returns to adoption for the gasoline engine truck and the disappearance of the electric truck. In his seminal work on path dependency, Paul David pointed out that random events, like a war in this case, can drive the industry

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<sup>8</sup> Mom, G. and Kirsch, D. (2001), p. 491

<sup>9</sup> *Ibid.*, p. 500

<sup>10</sup> *Ibid.*, p. 506

<sup>11</sup> *Ibid.*

<sup>12</sup> *Ibid.*

<sup>13</sup> *Ibid.*, p. 507

<sup>14</sup> *Ibid.*

<sup>15</sup> *Ibid.*, p. 492

<sup>16</sup> *Ibid.*, p. 510

into standardization on a system, which is inferior from a technological point of view.<sup>17</sup> Today, we are also on the cusp of a new revolution in freight transportation. Back then as well as today zero-emission drive concepts are attributed to be the future solution for urban applications. What makes us believe that now there is a window of opportunity for electric trucks to gain momentum in freight transport? The replacement from horse-drawn vehicles by gasoline-engine vehicles in freight transport has demonstrated that the transition process of a transport system is formed by factors like customer habits and preferences, market conditions, political regulations, developments in technology and infrastructure, cultural and symbolic meanings and power struggles between various actors.<sup>18</sup> Assessing ripeness of the transport business for electric mobility in the 21st century, therefore, requires an approach from different angles. The multi-level perspective (MLP) is such an approach and is used in this chapter to find significant indications that the era of electric trucks has begun. Particular focus is placed on cities, as they will play a fundamental role in establishing the future mobility regime. Cities increasingly carry out fleet tests with electric trucks to demonstrate their environmental and economic benefits.<sup>19</sup> In the context of the multi-level perspective, these demonstration projects are labelled niches, which form the seed-bed for future transitions.<sup>20</sup> Niches do not need to be demonstration projects necessarily but can have the form of “small market niches” or R&D laboratories for instance.<sup>21</sup> Their common denominator, however, is that they provide protected spaces, in which actors can learn about the “technology, user preferences, regulations, infrastructure, and symbolic meaning.”<sup>22</sup> These “incubation rooms”<sup>23</sup> for radical innovations are important because the electric truck is still inferior to the incumbent diesel truck with regard to technological and economic indicators like driving range and purchase price and therefore “cannot immediately compete on mainstream markets.”<sup>24</sup> A list of demonstration projects, which took part throughout the last years, can be found in the white paper of the International Council on Clean Transportation about the Transitioning to Zero-Emission Heavy-Duty

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<sup>17</sup> David, P. (1985), p. 335f.

<sup>18</sup> Geels, F. (2005), p. 446

<sup>19</sup> Daimler AG (2016b), URL see Bibliography

<sup>20</sup> Geels, F. (2005), p. 450

<sup>21</sup> Ibid.

<sup>22</sup> Ibid., p. 451

<sup>23</sup> Ibid., p. 450

<sup>24</sup> Ibid.

Freight Vehicles.<sup>25</sup> The supremacy of diesel engine trucks in freight transport is not only strengthened by economies of scale and its cost-lowering effect, but also by an existing diesel fuel infrastructure, legally binding regulations and laws that act as barriers to market entry, sunk investments, organizational commitments and self-interest of organizations, political lobbying and user habits and cognitive routines, which make stakeholders miss the opportunities outside their socio-technical regime.<sup>26</sup> Such mechanisms increased the returns of diesel engine truck adoption and led to the lock-in of freight transport into the diesel-based propulsion system.<sup>27</sup> One of the main bottlenecks of electric mobility is still the battery cost. But why should not the electric truck be capable of doing what the diesel truck once achieved, namely displacing an incumbent technology despite initial difficulties? Compared with gasoline trucks, diesel trucks were more expensive, heavier and less reliable due to technical problems like starting difficulties in cold weather.<sup>28</sup> Furthermore, there were not many fuel stations with diesel fuel and service stations that could maintain and repair diesel trucks.<sup>29</sup> But the positive characteristics of diesel trucks like lower fuel costs, long life and a dwindling price differential convinced more and more customers to turn their back on gasoline trucks.<sup>30</sup> In addition to that, the oil shock in 1973 spurred sales of diesel trucks, as diesel was a possibility to keep the operational costs low.<sup>31</sup> A lock-out from the existing socio-technical regime is therefore only possible if two conditions are fulfilled. First of all, the niche-innovations, which are still in their infancy phase, need to reach maturity in economic and technological terms. The expectation of Daimler Trucks that the battery cost will more than halve and the battery performance will more than double by the year 2025 compared to 1997 gives cause for optimism that electric mobility in freight operations, which has been hampered by the battery technology and costs so far, is gaining significant momentum.<sup>32</sup> The second condition is that the existing sociotechnical regime needs to be shaken to its very foundations by occurrences in the wider external environment, which is called the sociotechnical landscape in the theory of the multi-

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<sup>25</sup> Moultaq et. al (2017), p. 9-12

<sup>26</sup> Geels, F. (2012), p. 473

<sup>27</sup> Arthur, W. (1989), p. 116f.

<sup>28</sup> Laux, J. (1987), p. 100

<sup>29</sup> Ibid.

<sup>30</sup> Ibid., p. 106

<sup>31</sup> Ibid., p. 110

<sup>32</sup> Daimler AG (2016a), URL see Bibliography

level perspective<sup>33</sup>. And indeed, there are several landscape developments, which put pressure on the existing regime and could pave the way for the wider diffusion of novel propulsion technologies. It is already becoming apparent that cities respond to the growing air pollution, noise pollution and traffic jam caused by the increased freight transport demand by introducing Low or Zero Emission Zones with a complete or time-restricted ban on high-emission vehicles or by charging a fee depending on the level of greenhouse gas (GHG) and exhaust emissions of the truck. The British government has announced that it will ban diesel vehicle sales from 2040 onwards.<sup>34</sup> This ban only includes passenger vehicles and vans, but it can be expected that this ban will be extended to heavy goods vehicles (HGVs) someday. In light of global warming, the European Commission will further tighten the exhaust emissions and in future also regulate the CO<sub>2</sub> emissions and thus the fuel consumption of commercial vehicles. Heavy Duty Vehicles' (HDV) CO<sub>2</sub> emissions represent about one-quarter of road transport CO<sub>2</sub> emissions, which equals 6 percent of total EU greenhouse gas emissions.<sup>35</sup> In its Transport White Paper, the European Commission has set a long-term objective of overall EU transport greenhouse gas emissions reductions of about 60 percent in 2050 compared to 1990.<sup>36</sup> Furthermore, it is envisioned to “achieve essentially CO<sub>2</sub>-free city logistics in major urban centres by 2030”<sup>37</sup> what will trigger a shift towards electric trucks from 2020 onwards. This difficult state, in which the diesel based technology regime finds itself, is aggravated by the fact that the peak of conventional oil production will be reached in the future despite technological developments like the production of light tight oil (shale oil) or energy efficiency enhancements.<sup>38</sup> These circumstances cause tensions in the existing diesel-based technology regime, as incremental innovations cannot solve the problems. The result of these tensions is a crack in the existing regime which creates windows of opportunity for novel clean technologies to prosper and break out of their niches with the aim to become the new dominant technological regime. According to Unruh, who analysed the lock-in mechanisms in fossil fuel-based energy systems, this technological change will certainly occur.<sup>39</sup> It is only a matter of time. The question arises when this technological transition will likely occur and which important

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<sup>33</sup> Geels, F. (2011), p. 28f.

<sup>34</sup> Defra (2017b), p. 4

<sup>35</sup> European Commission (2018a), URL see Bibliography

<sup>36</sup> European Commission (2011), p. 3

<sup>37</sup> Ibid., p. 9

<sup>38</sup> International Energy Agency (2013), p. 447f.

<sup>39</sup> Unruh, G. C. (2002), p. 318

variables will foster and which variables will hinder the technological substitution process.

## 1.2 OBJECTIVE AND ORGANIZATION OF THE DISSERTATION

Enormous challenges lie ahead for the commercial vehicle industry and the trucking business. Governments are increasingly concerned about the environmental conditions in cities and will, therefore, regulate the commercial vehicle industry by imposing CO<sub>2</sub> emissions limits, introducing Low (LEZs) and Zero Emission Zones (ZEZs) and sharpening the limits for exhaust emissions. Truck manufacturers already started to respond to these challenges by presenting new truck models for urban delivery, which can drive emission-free.

The dissertation intends to analyse the adoption and temporal diffusion of electric rigid trucks in urban freight transport and these two terms can be defined as follows:

The diffusion process is concerned with the spread of a new product from its manufacturer to ultimate users or adopters. The adoption process, on the other hand, refers to the sequence of stages through which a consumer progresses from first awareness of an innovation to final acceptance.<sup>40</sup>

To understand the adoption and the diffusion of electric trucks, a discrete choice model and a diffusion model have been developed. The diffusion model is implemented as a System Dynamics model, which analyses the market uptake of electric trucks in the **United Kingdom** until 2050 and incorporates the feedback mechanisms like the development of battery costs depending on sales rates of electric trucks. Although the focus is on the United Kingdom, the results can be seen as representative for urban freight transport in the European Union as a whole. The analysed electric trucks are battery electric trucks, plug-in hybrid electric trucks and fuel cell electric trucks. The implementation of a CO<sub>2</sub> emissions limit and its effect on the uptake of electric trucks is investigated. Based on the estimated diffusion curves of electric trucks, a calculation of total CO<sub>2</sub> savings is made. Afterwards, the scenario technique is used, which allows to bundle the relevant characteristics of the

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<sup>40</sup> Mahajan, V. and Wind, Y. (1985), p. 2

influential variables in a scenario and to illustrate their impact in comparison with alternative developments, as there are considerable uncertainties concerning the further technical and cost development of the driving concepts as well as the development of the prospective customer behaviour and the framework conditions such as energy price trends and government subsidies and policies.

All economic, ecological, technical and legal aspects of the UK freight market have to be considered to be able to analyse the adoption and diffusion of electric trucks. Therefore, the **chapter 2** gives an outline of the UK freight market, describes which measures are already in place or will be taken in future to regulate the road freight transport and explains the technological possibilities to reduce the greenhouse gas emissions of commercial vehicles. The chapter concludes with a description of opportunities and barriers for electric mobility in urban road freight transport. Based on the findings from chapter 2, the adoption decision of truck customers is described with a discrete choice model in **chapter 3**. The core of the discrete choice model is the definition of the utility function, which includes all decision relevant product and truck customer attributes and which links these attributes to the utility of the truck customer.

**Chapter 4** integrates the customer adoption decision into a System Dynamics model, which describes the interactions between stakeholders of the urban freight transport market. Apart from the truck customers, the model contains the stakeholders government, truck manufacturer and infrastructure supplier. Different scenarios are tested in **chapter 5** to evaluate how the actions of these stakeholders can drive the urban freight market towards electric trucks.

Conclusions of the dissertation and an outlook for future research are given in **chapter 6** followed by a summary in **chapter 7**.

The following subchapter of the introduction will present the actual status of research and describe the research gap that this dissertation intends to close.

### 1.3 STATUS OF RESEARCH

There have been numerous studies, which investigated the CO<sub>2</sub> reduction and truck electrification potential of freight transport. Some studies described the barriers to adoption of CO<sub>2</sub> saving measures and electric trucks and presented ways to overcome these barriers. The most important of these studies will be shown here. This literature review is followed by an explanation of how this dissertation wants to fill the research gap.

The consultancy AEA Technology plc carried out a comprehensive study of the European heavy-duty vehicle market and about the technological options to reduce CO<sub>2</sub> emissions of freight activity. The study called “Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles – Lot 1: Strategy” calculated the reduction potential of greenhouse gas emissions by assuming uptake rates for fuel-saving technologies by 2030. The study concludes with a chapter on political instruments to tackle CO<sub>2</sub> emissions.<sup>41</sup>

Based on the data of the study mentioned above of AEA Technology plc and enriched by data from truck manufacturers, the technology development company TIAX LLC investigated the European Union (EU) greenhouse gas reduction potential for heavy-duty vehicles by the year 2030 and compared it with the potential for heavy-duty vehicles in the USA. The approach differs from the study of AEA Technology plc in that it uses a 2014 baseline vehicle meeting Euro 6 standard, whereas AEA Technology plc used a 2010 baseline vehicle meeting Euro 5 standard.<sup>42</sup> A further difference between these studies is that TIAX LLC bundles different individual fuel-saving technologies into technology packages and forecasts their adoption instead of making assumptions about the uptake of individual technologies like in the study of AEA Technology plc.<sup>43</sup> This approach results in calculations of different fuel consumption benefits. The study forecasts a slightly higher fuel reduction potential of 17 to 24 percent for the urban delivery segment than in the study of AEA Technology plc if a payback period of 3 years is expected.<sup>44</sup>

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<sup>41</sup> Hill et al. (2011), p. 1

<sup>42</sup> Law et al. (2011), p. 2-5

<sup>43</sup> Ibid., p. 7-1

<sup>44</sup> Ibid., p. 5-23

The European Commission contracted TU Graz to develop a test procedure for CO<sub>2</sub> emissions and fuel consumption of trucks. The test approach is described in “Reduction and Testing of Greenhouse Gas Emissions from Heavy Duty Vehicles - LOT 2” and is based on testing individual components like the driver cabin, vehicle body, engine and auxiliaries and simulating the fuel consumption and CO<sub>2</sub> emissions of the entire vehicle with these values.<sup>45</sup> As a result, realistic reference values for fuel consumption and CO<sub>2</sub> emissions can be simulated, which customers can take into account in their purchase decision.<sup>46</sup> The calculation of different CO<sub>2</sub> metrics is suggested to account for the huge variety of operations in freight transport. These metrics are g/(ton\*km) for driving with an average load, g/(ton<sub>max</sub>\*km) for driving at maximum payload, g/(m<sup>3</sup>\*km) for driving loaded to maximum available volume and g/km for driving empty<sup>47</sup>. This study was the basis for the simulation model VECTO, which will be used to certify heavy goods vehicles in Europe.

The overall aim of the study “Zukünftige Maßnahmen zur Kraftstoffeinsparung und Treibhausgasreduzierung bei schweren Nutzfahrzeugen”, which was carried out on behalf of the German Federal Environment Agency, was to estimate the fuel consumption reduction potential of a 40 t semi-trailer truck, a 12 t delivery truck and an 18 t city bus. The analysis for the 12 t delivery truck was performed with the simulation tool VECTO based on the mission profile Urban Delivery Cycle, and included only fuel-saving measures, which were sensible for urban distribution.<sup>48</sup> The analysis also included the examination of the fuel consumption reduction potential of trucks with alternative drivetrains. In addition to fuel benefits, the Well-to-Wheel greenhouse gas emission savings were determined. Furthermore, the study looked at the cost efficiency of the measures and identified technologies with future fuel cost savings exceeding the upfront cost within the assumed payback period of 3 years.<sup>49</sup> According to the study, the purchase of a 12 t battery electric truck would pay off in 7.5 years in the best case, what is still within the service life of the vehicle.<sup>50</sup>

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<sup>45</sup> University of Technology Graz (2012), p. 4f.

<sup>46</sup> Ibid., p. 34

<sup>47</sup> Ibid., p. 35

<sup>48</sup> Dünnebeil et al. (2015), p. 39

<sup>49</sup> Ibid., p. 106

<sup>50</sup> Ibid., p. 44

The International Council on Clean Transportation (ICCT) gave Ricardo Energy & Environment the task to investigate the future potential of fuel consumption reduction for heavy-duty vehicles up to 2030 in Europe. The study differentiates between the duty cycles Urban Delivery, Regional Delivery, and Long Haul and assigns a vehicle type to each duty cycle. Rigid panel vans with a gross vehicle weight between 3.5 t and 7.5 t represented urban delivery, whereas a 12 t rigid box-truck was chosen to represent regional delivery.<sup>51</sup> The study includes all fuel-saving technologies that were considered in the CO<sub>2</sub> legislation Phase II for heavy-duty vehicles in the United States (US).<sup>52</sup> Consideration of all possible measures, regardless of payback requirements, can lead to savings of 44.7 percent for the rigid panel van and 31.7 percent for the rigid box-truck.<sup>53</sup> The highest contributor to fuel improvements for urban rigid panel vans was the full hybridization with a 28 percent fuel consumption benefit.<sup>54</sup>

The company Ricardo-AEA Ltd. examined the opportunities to overcome the barriers to uptake of low emission technologies for different commercial vehicle duty cycles. From a technological and economic point of view, the report chose the technologies start/stop and idle shut-off, hybrid electric and flywheel hybrid vehicles, natural gas engine and pure electric vehicles as suitable for further investigation for urban delivery operations.<sup>55</sup> The result of interviews and an online survey with fleet operators was that the main obstacle hindering the diffusion of a new technology is the uncertainty whether its adoption is profitable.<sup>56</sup> For battery electric and hybrid electric trucks, high truck prices, doubts about fuel savings, residual values, payback periods, range and reliability and worries about charging requirements and payload decrease were prevalent.<sup>57</sup> Examples of opportunities to overcome these concerns are higher payload allowances for electric vehicles and subsidies for the purchase of electric vehicles.<sup>58</sup>

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<sup>51</sup> Norris, J. and Escher, G. (2017), p. 5

<sup>52</sup> Ibid., p. 27

<sup>53</sup> Ibid., p. 89f.

<sup>54</sup> Ibid.

<sup>55</sup> Kay, D. and Hill, N. (2012), p. 5

<sup>56</sup> Ibid., p. ii

<sup>57</sup> Ibid., p. 7f.

<sup>58</sup> Ibid., p. 10

Another study which examines the barriers to adoption of fuel-saving technologies based on a survey and interviews comes from CE Delft. Examples of barriers are the lack of information on the fuel savings of individual technologies and limited access to financial instruments.<sup>59</sup>

Following the report mentioned above, CE Delft published a report about the potential of battery electric and fuel cell electric trucks. After having described the technologies elaborately, the authors conclude that the battery electric truck can be a promising alternative to the diesel truck for short distance applications due to low daily mileage and scheduled overnight parking.<sup>60</sup> For long distance applications, the battery electric truck is for now only feasible if the electricity comes from inductive charging or catenary wires, as otherwise, the battery would weigh too much.<sup>61</sup>

In the white paper “The Future of Trucks”, the authors argue that the “support for alternative fuels and vehicles needs to cover four main areas: RD&D, market uptake of alternative fuel vehicles, adequate access to charging or refuelling infrastructure and the availability of alternative energy carriers.”<sup>62</sup>

Lew Fulton and Marshall Miller from the University of California Davis published a white paper about the “Strategies for Transitioning to Low-Carbon Emission Trucks in the United States.”<sup>63</sup> A key finding of the paper is that a deep reduction in carbon emissions needs a strong uptake of zero-emission trucks and advanced biofuels. This high level of diffusion of zero-emission trucks and alternative fuels is only achievable if, in addition to the existing truck fuel economy standards, policies like the support for RD&D projects, ZEV standards, the roll-out of the hydrogen and electricity infrastructure, the supply of advanced biofuels and pricing policies are in place.<sup>64</sup>

Jesper Brauer uses the Bass diffusion model in his master thesis to analyse when the hybrid technologies are going to dominate the heavy-duty vehicle market. The

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<sup>59</sup> Aarnink et al. (2012), p. 7f.

<sup>60</sup> den Boer et al. (2013), p. 7

<sup>61</sup> Ibid.

<sup>62</sup> Teter et al. (2017), p. 10

<sup>63</sup> Fulton, L. and Miller, M. (2015), p. 2

<sup>64</sup> Ibid., p. 39-43

forecasting of the diffusion of a product with the Bass model requires knowledge of the Bass model coefficients. These coefficients are generally estimated based on historical sales data of the new product. As these data were not given, Brauer used analogous products, which share characteristics with the new product and for which sales data existed, to obtain the innovation and imitation parameters of the Bass diffusion model. The analogous products chosen were radial tyre, disc brake and anti-lock brak system.<sup>65</sup>

The doctoral dissertation of Claudio Seitz about the diffusion of innovative drivetrain technologies to reduce the CO<sub>2</sub> output of commercial vehicles is the first work which approaches the topic with scientific methods. Conjoint analysis is used to understand the purchase behaviour of truck customers. The diffusion of innovative drivetrain technologies for Germany is simulated with a System Dynamics model.<sup>66</sup>

The second academic work that uses scientific methods to investigate the diffusion of electric trucks in freight transport is the research report “Truck Choice Modeling: Understanding California's Transition to Zero-Emission Vehicle Trucks Taking into Account Truck Technologies, Costs and Fleet Decision Behavior” from researchers of the University of California Davis. They are the first to use a discrete choice model that includes factors like purchase price, maintenance and fuel costs, infrastructure availability or incentives and subsidies for the modelling of the purchase decision process.<sup>67</sup>

There are several studies from management consulting firms about the truck market. The two latest ones by McKinsey & Company and Roland Berger Strategy Consultants are briefly sketched out. The authors of the McKinsey study indicate that radical shifts in the trucking industry will occur until 2025 and describe in detail the six trends, which they believe will drive this transformation. Keywords associated with this transformation are automated driving, connectivity, drones, autonomous delivery robots, 3-D printing, sustainability, new urban consumer demands, new players and new business models.<sup>68</sup> Regulation of greenhouse gas emissions of commercial vehicles and driving bans for urban centers will force logistics providers to invest in

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<sup>65</sup> Brauer, J. (2011), p. 36f.

<sup>66</sup> Seitz, C. (2015), p. 10

<sup>67</sup> Miller et. al (2017), p. 3

<sup>68</sup> Kässer et al. (2016), p. 16-28

electric vehicles.<sup>69</sup> According to the study of Roland Berger Strategy Consultants, which was carried out for automotive companies and fuel suppliers, a cost-efficient reduction of greenhouse gas emissions from commercial transport is possible by increasing the uptake of biofuels and the efficiency of diesel engines, promoting alternative drivetrains and allowing trucks a higher weight and maximal length.<sup>70</sup> The authors believe that sales of hybrid electric and battery electric trucks can reach 8 percent of total registrations in the medium-duty vehicle (MDV) sector by 2030.<sup>71</sup>

Shell Deutschland Oil GmbH published its first study on the commercial vehicle sector in 2010. The follow-up study, which investigates the freight market for Germany up to 2040, was published in 2016. The conclusion of the study is that plug-in hybrid electric trucks, battery electric trucks and compressed natural gas trucks will account for 22.4 percent of the medium-duty vehicle market by 2040 if customers change their purchase behaviour, the new technologies develop accordingly and the framework conditions like political regulations or fuel prices are in favour of alternative drivetrains.<sup>72</sup> Otherwise, the market share of alternative drivetrains is likely to stay under the 10 percent mark.<sup>73</sup>

Researchers from Portland State University published several papers in which they compare conventional and electric commercial vehicles for the US market and work out the economic and technological factors that affect the competitiveness of electric vehicles.<sup>74; 75</sup> Therefore they use an integer programming model and make a break-even analysis under different scenarios and conclude that firm-specific factors like planning time horizon, annual mileage and discount rate and vehicle-related factors like electric truck price and diesel truck fuel economy affect the outcome of the comparison.<sup>76</sup>

All these studies build upon the notion that truck customers have perfect information about the drivetrain options when making a purchase decision. The consequence is

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<sup>69</sup> Kässer et al. (2016), p. 23

<sup>70</sup> van der Slot et al. (2016), p. 13

<sup>71</sup> Ibid., p. 51

<sup>72</sup> Adolf et al. (2016), p. 16

<sup>73</sup> Ibid.

<sup>74</sup> Feng, W. and Figliozzi, M. (2012), p. 702

<sup>75</sup> Feng, W. and Figliozzi, M. (2013), p. 135

<sup>76</sup> Ibid., p. 145

that the electrification potential of freight transport is overestimated. In reality, truck customers might behave rationally inattentive. They have limited time and money resources and probably cannot acquire all information when evaluating the attractiveness of drivetrain options. As a consequence, a rest uncertainty remains when making purchase decisions, and truck customers might miss the chance to invest in a truck that provides the highest utility to them. This behaviour is in line with the so-called energy efficiency paradox in freight transport.

Rational inattention theory is increasingly becoming popular in studies about consumers' valuation of product characteristics in choice experiments.

Sallee analysed if consumers are rational inattentive to the energy efficiency of durable goods in their purchase decision and found out that consumers are less likely to acquire information on the energy efficiency of cars "when the variance of energy savings across models in a class is small and when the variance of other attributes is large."<sup>77</sup> The study by Sallee did not include alternative drivetrain technologies.

Leard investigated passenger car buyers' inattentiveness towards fuel cost savings using conditional and mixed logit models.<sup>78</sup> Although the choice set includes different drivetrain technologies like an electric vehicle or hybrid vehicle, Leard also focuses solely on customers' inattentiveness towards fuel cost savings. However, customers could also be inattentive to other characteristics of electric vehicles like the driving range, charging time or charging infrastructure coverage. Leard compares the estimated willingness to pay for fuel cost savings to the fuel cost savings that are realistically achievable over the lifetime of the vehicle.<sup>79</sup> The results are that customers who stated to be inattentive to fuel costs during a purchase decision undervalue the savings, which means that the willingness to pay value is smaller than the achievable fuel cost savings.<sup>80</sup> One explanation for the inattentiveness of customers towards fuel cost savings is the factor 'vehicle miles travelled'.<sup>81</sup> In cases

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<sup>77</sup> Sallee, J. M. (2012), p. 1

<sup>78</sup> Leard, B. (2018), p. 8

<sup>79</sup> Ibid., p. 1

<sup>80</sup> Ibid., p. 1 f.

<sup>81</sup> Ibid., p. 2

where the 'vehicle miles travelled' is low, the decision to be inattentive can be treated as rational.<sup>82</sup>

There has not been any scientific work yet that developed a Discrete Choice Model including information frictions for the analysis of the adoption of electric trucks in urban freight transport and that used a System Dynamics model including rational inattention of truck customers to investigate the diffusion of electric trucks in the freight market. This dissertation intends to close this research gap.

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<sup>82</sup> Leard, B. (2018), p. 2

## **2. DIFFUSION OF ELECTRIC TRUCKS IN URBAN FREIGHT TRANSPORT IN THE UNITED KINGDOM**

Trucks are one of the physical backbones of the economy. They are used in various transport activities like urban delivery of clothes and food, money transfer between banks or for fire- and emergency operations. It is evident that the economic cycle would stop without trucks. Road freight vehicles handle the lion's share of freight transport in the UK. Other freight transport modes account only for a small fraction of all transported goods.<sup>83</sup> The urban population in the UK steadily grew over the last years, and this trend will hold on.<sup>84</sup> A growing urban population implies increased demand for goods, which have to be transported into and within cities. However, trucks produce significant amounts of greenhouse gas and pollutants, noise, and congestion. The following chapters will give an overview of the UK freight market followed by the explanation of regulative and technical measures that can curb the emissions of pollutants and greenhouse gases of the road freight transport.

### **2.1 URBAN-DELIVERY AND THE UK FREIGHT MARKET**

Commercial Vehicles with a gross vehicle weight greater than 3.5 t are called heavy goods vehicles (HGVs), whereas commercial vehicles with a gross vehicle weight of less than 3.5 t are called light goods vehicles (LGVs). The Gross Vehicle Weight (GVW) is the maximum allowable weight of the vehicle including the payload<sup>85</sup> and should not be exceeded due to safety reasons. Furthermore, overloading leads to road wear and tear and is unfair to operators, which stick to the legally binding weight restrictions.<sup>86</sup> Commercial vehicles in Europe are classified into three categories depending on their Gross Vehicle Weight:

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<sup>83</sup> Wilkins et al. (2016), p. 102

<sup>84</sup> Office for National Statistics (2016), URL see Bibliography

<sup>85</sup> Teter et al. (2017), p. 16

<sup>86</sup> Department for Transport (2003), p. 2

“Category N: Motor vehicles with at least four wheels designed and constructed for the carriage of goods.

- Category N1: Vehicles designed and constructed for the carriage of goods and having a maximum mass not exceeding 3,5 tonnes.
- Category N2: Vehicles designed and constructed for the carriage of goods and having a maximum mass exceeding 3,5 tonnes but not exceeding 12 tonnes.
- Category N3: Vehicles designed and constructed for the carriage of goods and having a maximum mass exceeding 12 tonnes.”<sup>87</sup>

The following Table 1 shows the different fields of application of commercial vehicles and their characteristics.

<p><b>Duty Cycle Characteristics</b></p>
<p><b><u>Long-distance Transport:</u></b></p> <ul style="list-style-type: none"> <li>- “Delivery to national and international sites (mainly highway operation and a small share of regional roads)”<sup>88</sup></li> <li>- 33-44 t gross vehicle weight, London-Edinburgh, highway 800miles/day, 50,000-150,000 miles/year, high variability of routes, very price sensitive, fuel intensive, partially environmentally sensitive</li> </ul>
<p><b><u>Regional-Transport:</u></b></p> <ul style="list-style-type: none"> <li>- “Regional delivery of consumer goods from a central warehouse to local stores (inner-city, suburban, regional and also rural and mountainous roads)”<sup>89</sup></li> <li>- “A mixture of rigid and articulated trucks. Rigid are typically 18-26 tonnes...articulated trucks up to the maximum 44 tonnes, particularly for supermarkets making deliveries from regional distribution centres”<sup>90</sup>, 30-120 miles/tour, 200-300 miles/day, 18,000-75,000 miles/year, very price sensitive, partially environmentally sensitive.</li> </ul>

<sup>87</sup> Department for Transport (2017b), URL see Bibliography

<sup>88</sup> Kay, D. and Hill, N. (2012), p. 13

<sup>89</sup> Ibid., p. 2

<sup>90</sup> Ibid., p. 12

**Urban-Delivery:**

- “Urban delivery of consumer goods from a central store to selling points (inner-city and partly suburban roads)”<sup>91</sup>
- Mostly rigid trucks under 18 tonnes, 10-30 miles/tour, 125 miles/day, 15,000-40,000 miles/year<sup>92</sup>, environmentally sensitive, partially high variability of routes, high energy demand for auxiliary units (also in stationary mode)

**Municipal Delivery:**

- “Urban truck operation like refuse collection (many stops, partly low vehicle speed operation, driving to and from a central base point) [...] Rigid vehicles, mainly refuse collection vehicles (RCVs) mostly at 26 tonne, but also street sweepers mostly at 15 tonnes”<sup>93</sup>
- Start-Stop traffic, 30-90 miles/day, 5,000-18,000 miles/year<sup>94</sup>, environmentally sensitive, high energy demand for auxiliaries

**Construction Industry:**

- “Construction site vehicles with delivery from central store to very few local customers (inner-city, suburban and regional roads; small share of off-road driving)
- Primarily rigid tipper lorries (small - up to 7.5 tonne) and large (over 26 tonne); articulated tippers...some flat-beds; skip loaders; concrete mixers etc.”<sup>95</sup>
- Truck with a lifting platform, 30-90 miles/day, rigid trucks with 14,000-30,000 miles/year, artics up to 45,000 miles<sup>96</sup>, robustness is important, high energy demand for auxiliaries

Table 1 Areas of application for commercial vehicles<sup>97; 98</sup>

Urban delivery can be further split into the three market sectors ‘Retail’, ‘Courier, Express and Parcel’ (CEP) and ‘Hotels, Restaurant and Catering’ (HoReCa).<sup>99</sup> E-Commerce, which is continuously gaining popularity and increasing the freight traffic in cities, can be allocated to both Retail and Courier, Express and Parcel. Commercial electric vehicles have already been deployed in different logistics operations like cash

<sup>91</sup> Kay, D. and Hill, N. (2012), p.12

<sup>92</sup> Ibid.

<sup>93</sup> Ibid., p. 13

<sup>94</sup> Ibid.

<sup>95</sup> Ibid., p. 14

<sup>96</sup> Ibid.

<sup>97</sup> Daimler AG

<sup>98</sup> Kay, D. and Hill, N. (2012), p. 12-14

<sup>99</sup> Behrends, S. (2016), p. 280f.

deliveries, grocery deliveries, home shopping deliveries, postal services and urban deliveries of different goods.<sup>100</sup>

According to statistics from the European Automobile Manufacturers' Association (ACEA), the UK freight market was the second biggest regarding new sales of heavy goods vehicles greater than 3.5 t after Germany in 2015. France, Spain, and Poland followed these two markets. The remaining European markets are rather small but made up together approximately 22 percent of the total heavy goods vehicles sales in 2015 (see Figure 1).

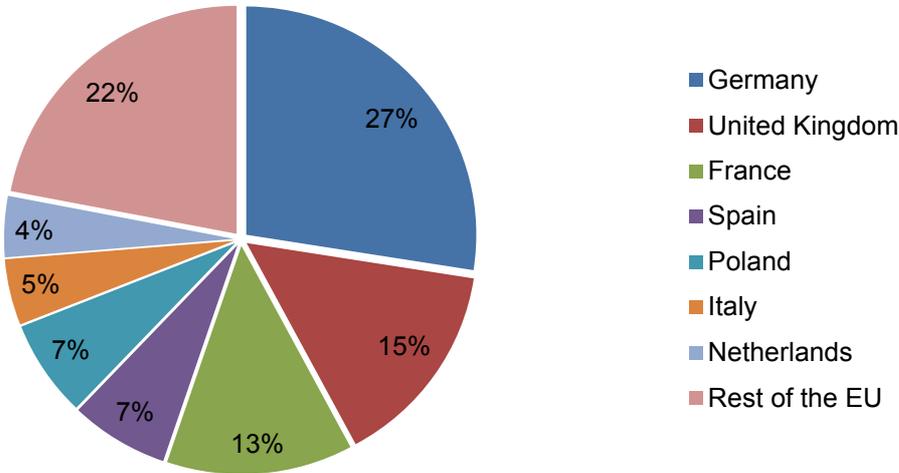


Figure 1 Heavy goods vehicles' sales market share in the EU in 2015<sup>101</sup>

As can be seen in Figure 2, the market for heavy goods vehicles in the UK is strongly consolidated and is mainly shared between 8 manufacturers. DAF, SCANIA, DAIMLER, and VOLVO together had a market share of 73.9 percent in 2016. All of the manufacturers offer electric trucks. Besides the manufacturers shown in the graph, there are niche players like Smith Electric Vehicles, which have extensive experience in the development and manufacturing of electric trucks.

<sup>100</sup> Margaritis et al. (2015), p. 4

<sup>101</sup> ACEA (2016a), MCV (6) and HCV (9) tabs, URL see Bibliography

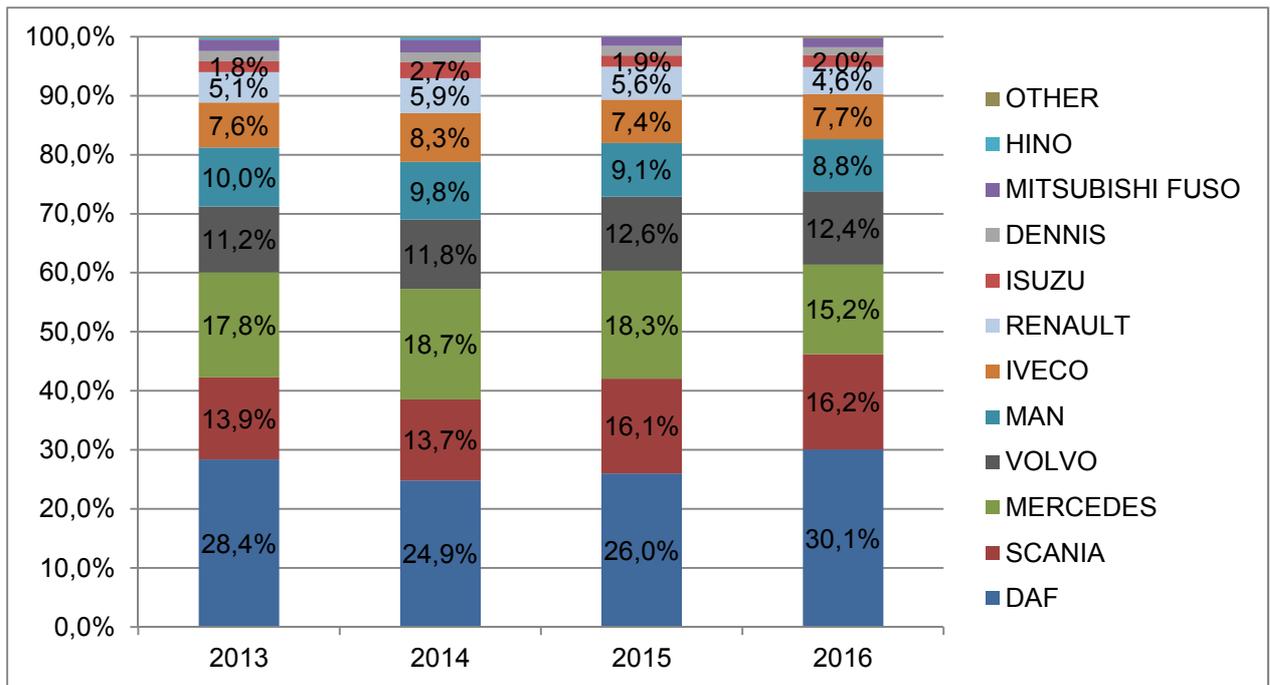


Figure 2 Heavy goods vehicles' sales market share over 6 t in the UK between 2013 and 2016 by manufacturers<sup>102; 103</sup>

According to statistics from the Department for Transport, there were 517,100 licensed heavy goods vehicles in the United Kingdom in 2016 with following shares of different weight categories (see Figure 3).

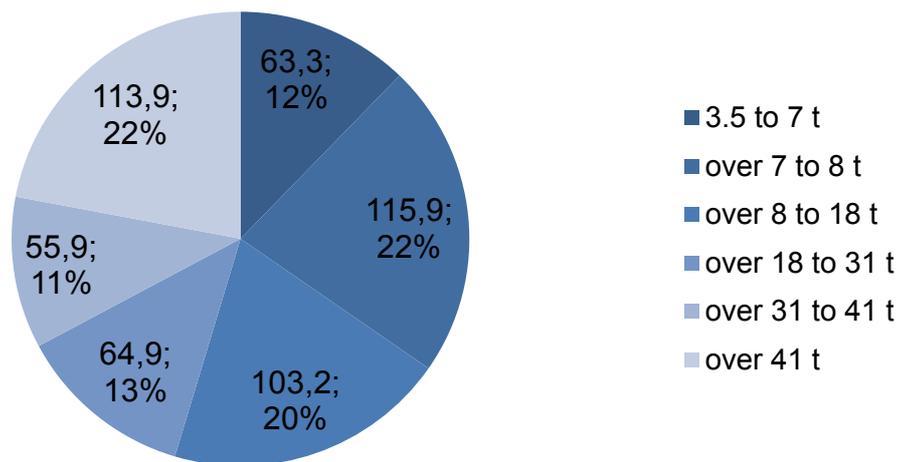


Figure 3 Licensed vehicles in the UK in 2016 in thousand<sup>104</sup>

<sup>102</sup> SMMT (2017), URL see Bibliography

<sup>103</sup> MotorTransport (2016), p. 30

Rigid Vehicles constitute the largest part of the UK commercial vehicle fleet. The dissertation follows the approach used in the study of Ricardo-AEA to determine the number of licensed rigid vehicles, which are deployed in urban delivery. To this end, it is necessary to allocate the total number of rigid vehicles to the five duty cycles. At the end of the year 2016, there were 294,000 rigid trucks licensed in the UK, what represented more than half of the total heavy goods vehicles stock (see Figure 4).

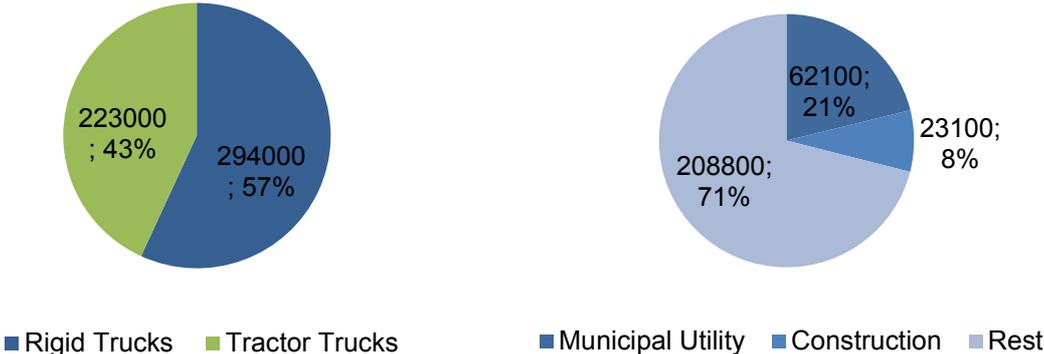


Figure 4 Share of rigid trucks in vehicle stock in 2016 and allocation of rigid trucks to duty cycles<sup>105</sup>

In contrast to tractor trucks, the body of the rigid trucks is attached to the chassis.<sup>106</sup> The areas of application from rigid trucks range from distribution and refuse disposal to street cleansing and construction. This fact explains the variety of body types of rigid trucks, like curtain sider, tanker, concrete mixer or tipper.<sup>107</sup> Lighter rigid trucks make the biggest portion of all licensed rigid trucks. The share of rigid trucks with a gross vehicle weight up to 7.5 t dropped in the last years, whereas the market shares of the other weight classes increased slightly (see Figure 5). The market shares of different weight categories in a country are dependent on various factors like:

geography; population density and distance among many centres of raw material production, industrial processing and consumption; the level and rate of urbanisation; country size; the share of light and heavy industry, services, and agriculture in the economy; the development of the railway sector; and regulations and restrictions on trucking, rail and inland freight.<sup>108</sup>

<sup>104</sup> Department for Transport (2017d), URL see Bibliography  
<sup>105</sup> Department for Transport (2017c), URL see Bibliography  
<sup>106</sup> Muncrief, R. and Sharpe, B. (2015), p. 8  
<sup>107</sup> Department for Transport (2017c), URL see Bibliography  
<sup>108</sup> Teter et al. (2017), p. 30

In countries with a high urbanisation rate like the UK, the share of light goods vehicles is higher.<sup>109</sup>

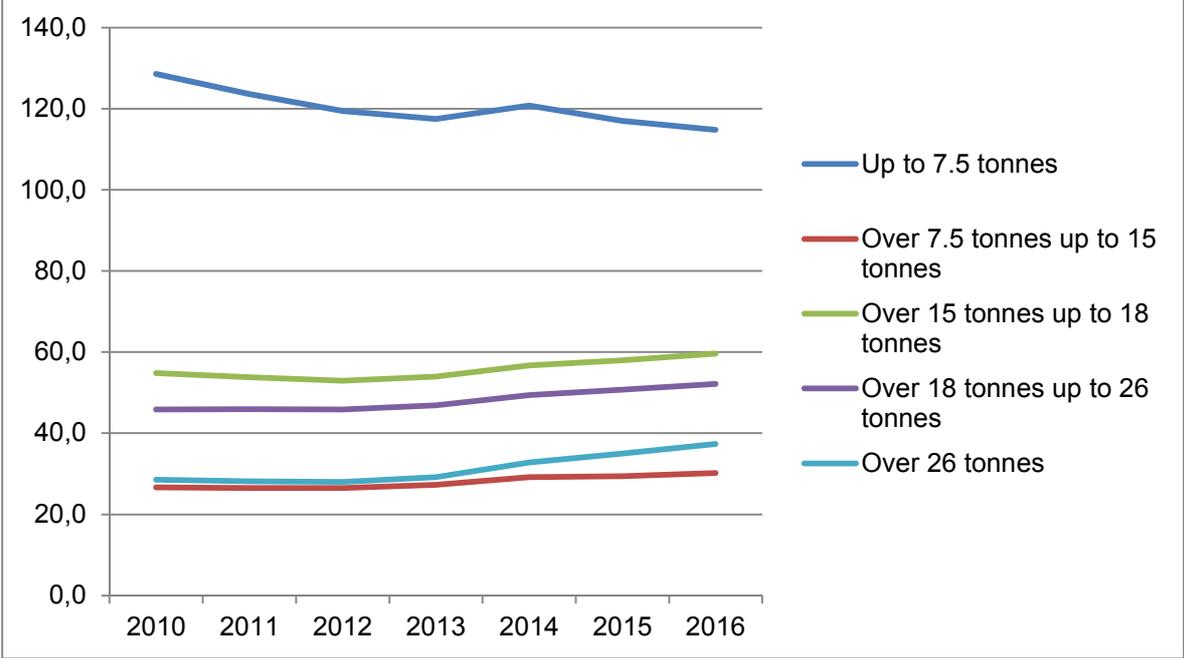


Figure 5 Rigid truck registrations in thousand in the UK between 2010 and 2016<sup>110</sup>

The calculation of the number of rigid trucks, which are deployed in urban transport, required the determination and exclusion of all rigid trucks, which are used in the municipal utility duty cycle and the construction duty cycle, in the first place. In the licensing statistics of the Department for Transport (DfT), these trucks are listed as refuse disposal and street cleaning trucks.<sup>111</sup> Also, trucks listed as tipper trucks, skip loader trucks, and concrete mixer trucks were removed from the list, to exclude the construction duty cycle.<sup>112</sup> The stock of rigid trucks (208,800 trucks) which then remained was allocated to urban delivery, regional delivery and long-haul transport using the estimated percentage splits of the Ricardo-AEA study (see Table 2).

<sup>109</sup> Teter et al. (2017), p. 30

<sup>110</sup> Department for Transport (2017c), URL see Bibliography

<sup>111</sup> Ibid.

<sup>112</sup> Ibid.

Duty Cycle	Rigids					Total Rigid
	>3.5 t to 7.5 t	>7.5 t to 15 t	>15 t to 18 t	>18 t to 26 t	>26 t	
Urban Delivery	80%	60%	30%	10%	-	51.92%
Regional Transport	20%	40%	70%	80%	80%	45.65%
Long Haul	-	-	-	10%	20%	2.43%

Table 2 Allocation of rigid trucks to duty cycles in percent<sup>113</sup>

Urban delivery rigid trucks with a gross vehicle weight ranging from 3.5 t to 26 t make up nearly 52 percent of all rigid trucks (208,800 trucks). This approach results in 108,409 rigid trucks deployed in urban delivery. The rest of the vehicle stock is used for regional and long-haul transport. With the exclusion of the construction and municipal utility duty cycles (85,200 trucks), the allocation of the total rigid vehicle stock to duty cycles is as shown in Figure 6. According to the study, rigid trucks with a gross vehicle weight greater than 26 t are not used for urban delivery. Mainly lighter rigid vehicles are used for urban delivery. The employment rates of rigid trucks for urban delivery decreases with increasing GVW. In the study of Dünnebeil et al., the 12 t delivery was chosen as representative of rigid trucks between 7.5 t and 18 t.<sup>114</sup> This dissertation extends this classification to include the lower and upper end of the weight range of rigid trucks. Therefore, the delivery truck with a box body is chosen as representative for rigid trucks from 3.5 to 26 t. All truck related technical and economic data given in the dissertation refer to this specific truck type. This simplification to a standard 12 t distribution truck with a box body is chosen for the diffusion modelling, as the 12 t truck alone has more than 1,000 variants due to different specifications of truck parts like the engine or cabin size, and extra components like added tanks.<sup>115</sup> Including the different weight categories and body types would even further complicate the modelling process.

<sup>113</sup> Kay, D. and Hill, N. (2012), p. 15

<sup>114</sup> Dünnebeil et al. (2015), p. 39

<sup>115</sup> Ibid., p. 36

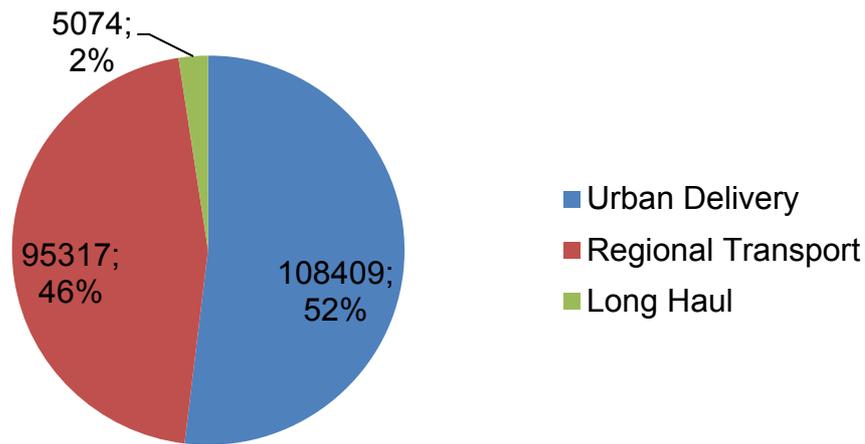


Figure 6 Allocation of total rigid trucks to duty cycles

According to the statistics from the Department for Transport, 35 Ultra Low Emission Vehicles (ULEV) were registered in the years between 2010 and 2016. The Department for Transport uses the term ULEV for Battery Electric Vehicles (BEV), Fuel Cell Electric Vehicles (FCEV) and Plug-in Hybrid Vehicles (PHEVs). Nine out of these 35 have been registered in 2016, which could be seen as an indicator of increased interest in electric mobility. For reasons of simplification, the initial stock of electric trucks is set to zero for the simulation runs. The share of the different fleet categories in the market is given in the study “Overview of the UK Commercial Vehicle Industry”. According to this study, the percentage shares of the number of licenses and vehicles depending on fleet size in 2015 were as follows:

Fleet Size	Share of licenses	Share of vehicles
1	42%	9.07%
2 to 5	32%	19.91%
6 to 10	7.46%	12.21%
11 to 20	4.17%	13.08%
21 to 50	2.54%	17.13%
51 plus	1.14%	28.58%

Table 3 Fleet size distribution in the market<sup>116</sup>

<sup>116</sup> MotorTransport (2016), p. 9

One can see from Table 3 that operators with less than five trucks accounted for the biggest share of the total operators. Nevertheless, operators with more than 51 trucks, which made up a tiny portion of all operators, nearly possessed 30 percent of all licensed vehicles. Europe-wide, the share of freight operators with less than ten vehicles among all freight operators is 85 percent.<sup>117</sup>

What makes transport in urban areas interesting as the object of investigation is that it is going to face the highest pressure of change due to regulatory measures. Cities like London face severe congestion and air quality problems as a result of a high transport volume. Besides their contribution to global warming due to the emission of greenhouse gas, trucks are criticized for their high noise pollution and for posing a potential hazard to cyclists and pedestrians.<sup>118</sup>

Electric delivery trucks fit perfectly with the hub-and-spoke concept, which is gaining importance in urban freight transport. In this concept, goods are transported with large tractor-trailers to logistic hubs on the outskirts, where they are transferred to lighter trucks, which then bring the goods to their destinations in the city. Goods are transported a distance of 26 km on average in London<sup>119</sup>, and longer journeys exceeding 80 miles (approximately 129 km) are not typical.<sup>120</sup> Therefore, a driving range of 130 km and a single charge will be sufficient to accomplish most transport tasks in cities. Thus, electric trucks are ideally suited for this last-mile delivery task, as the shorter driving distances do not limit the application potentials of electric trucks.<sup>121</sup> Furthermore, they can drive into Zero Emission Zones without having to pay any charge. Sadiq Khan, the mayor of London, already announced the implementation of a Zero Emission Zone in Central London in 2025. The difference between the Ultra Low Emission Zone (ULEZ) and the Zero Emission Zones is that only emission-free vehicles are allowed to drive in Zero Emission Zones, whereas in Ultra Low Emission Zones vehicles which fulfill a defined emission standard are allowed to drive. The Zero Emission Zones shall be extended to central London by 2040, and the ultimate goal is to have an emission-free zone for London as a whole by 2050.<sup>122</sup> It can be expected that other world cities will follow. In general, there exist two different transport tasks in

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<sup>117</sup> European Commission (2018b), URL see Bibliography

<sup>118</sup> Lord, O. (2017), p. 20

<sup>119</sup> Gota, S. and Wang, B. (2017), p. 20

<sup>120</sup> Worthy et al. (2015), p. 4

<sup>121</sup> Raiber et al. (2014), p. 7

<sup>122</sup> FleetNews (2017), URL see Bibliography

urban areas (see Figure 7). In single-point delivery, the truck delivers one or maximum two stores in the Zero Emission Zone and drives out the Zero Emission Zone after completion of the task. The operation mode in the Zero Emission Zone is all-electric, whereas the truck switches to diesel mode outside the Zero Emission Zone. The driving range in the Zero Emission Zone is up to 20 km. Plug-in hybrid electric trucks would be ideally suited for this task. A typical representative of this transport task is the delivery of stores like Tesco. In multi-point delivery, the vehicle drives a round trip in the Zero Emission Zone. The vehicles operate only in urban areas, and the driving range is between 20 and 80 km. The higher driving ranges would require the deployment of a battery electric truck in a Zero Emission Zone. A typical representative of this task is the delivery service of a UPS truck.

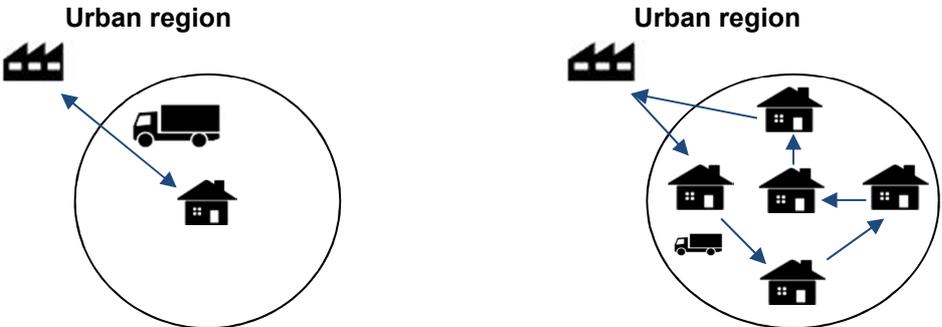


Figure 7 Single-point delivery and multi-point delivery<sup>123</sup>

The rise of e-commerce will inevitably lead to an increase in delivery traffic in urban regions and an aggravation of the associated problems like global warming and unhealthy air quality.

## 2.2 GLOBAL WARMING AND AIR QUALITY IN CITIES

Road freight vehicles are a significant producer of pollutants and are responsible for 25 percent of total road transport emissions, which is equivalent to 6 percent of total CO<sub>2</sub> emissions in the European Union.<sup>124</sup> Worldwide, about half of the produced diesel

<sup>123</sup> Daimler AG

<sup>124</sup> European Commission (2018a), URL see Bibliography

is burnt in road freight vehicles to transport goods to their final destinations, and road freight vehicles users are responsible for one-fifth of global oil demand and are the primary driver of global diesel demand since 2000.<sup>125</sup> With impressive numbers like these, it is evident that the freight transport market needs to be and will be regulated. By reducing the amount of oil consumption and using renewably produced electricity or hydrogen, freight transport can significantly contribute to energy security and reduce the dependence on oil-producing countries. The following chapters will give an overview of the environmental consequences of diesel use in road freight vehicles and explain which regulations are already in place or will be introduced to limit the emissions of road freight transport. Furthermore, technical measures will be described, which can lead the way to a greener freight transport.

### 2.2.1 CO<sub>2</sub> EMISSIONS LIMIT AND VECTO: TACKLING GLOBAL WARMING

The Paris Agreement is the first climate deal, which was reached by consensus of all countries of the world. It was adopted in December 2015 at the Paris Climate Conference and its objective is to avoid climate change by limiting the temperature increase to less than 1.5 degrees Celsius above the temperature level that existed before the industrial age.<sup>126</sup> In line with this goal, the European Commission has published a strategy for low-emission mobility that sets out the path to reach the climate goals of the EU.<sup>127</sup> It envisions the shift of the transport sector, which currently heavily relies on fossil fuels, to a highly resourceful transport system by deploying digital technologies, supporting the use of alternative energy forms like biofuels or renewable electricity, accelerating the diffusion of low emission vehicles and moving the cities to apply measures with regard to environmental targets.<sup>128</sup> This step has long been overdue, as other Triad markets like USA, Japan or Canada already have taken action in that direction. Japan was the first country to regulate CO<sub>2</sub> emissions in

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<sup>125</sup> Teter et al. (2017), p. 9

<sup>126</sup> European Commission (2017a), URL see Bibliography

<sup>127</sup> European Commission (2016), URL see Bibliography

<sup>128</sup> Ibid.

2007, followed by the USA in 2011 and Canada in 2012.<sup>129</sup> China implemented a regulation on CO<sub>2</sub> emissions in 2015. India and Mexico recently introduced a fuel consumption regulation for commercial vehicles in 2017 and 2018 respectively, while Russia and South Korea are considering the adoption of fuel consumption standards.<sup>130</sup> By setting CO<sub>2</sub> standards, the European Union pursues the objective to keep its position as the leader in manufacturing fuel-efficient heavy-duty vehicles.<sup>131</sup> In the following, the fuel economy standards of Japan, the USA, and China will be sketched out briefly. Afterwards, the European approach to regulate CO<sub>2</sub> emissions of heavy goods vehicles will be presented.

### **Japanese approach – Fuel Economy Standard**

The fuel economy targets are determined with the top-runner approach, what means that vehicles with the best performance are used as a reference for standards.<sup>132</sup> The targets became effective fully in 2015 and are dependent on the weight of the truck. In contrast to the USA, where the engine and heavy-duty manufacturers usually are separate entities, the vertical integration of these two is more common in Japan.<sup>133</sup> That is why the fuel economy standard in Japan applies directly to the manufacturer.<sup>134</sup> Two of the main points of critique of the Japanese approach is that it only considers improvements in engine and transmission technology and excludes other fuel-saving measures like aerodynamic improvements and that only the two drive cycles urban driving mode and interurban driving mode are represented.<sup>135</sup> To account for the significant fuel consumption reduction potential of hybrid electric trucks, a separate hardware-in-the-loop simulation (HILS) testing for this vehicle type was developed.<sup>136</sup>

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<sup>129</sup> European Commission (2014), p. 4

<sup>130</sup> European Commission (2018b), URL see Bibliography

<sup>131</sup> Ibid.

<sup>132</sup> Teter et al. (2017), p. 44

<sup>133</sup> THE NATIONAL ACADEMIES PRESS (2010), p. 42

<sup>134</sup> Ibid.

<sup>135</sup> Ibid.

<sup>136</sup> Ibid.

## **US approach – National Program Phase I and Phase II**

The two main parties involved in the definition of fuel efficiency standards in the USA are the National Highway Traffic Safety Administration (NHTSA) and the Environmental Protection Agency (EPA). The National Highway Traffic Safety Administration is responsible for setting fuel efficiency standards, whereas the Environmental Protection Agency has the duty to set CO<sub>2</sub> emission standards.<sup>137</sup> The National Highway Traffic Safety Administration and the Environmental Protection Agency developed a fuel efficiency standard called HD National Program, which was established in 2011 and covers Heavy Duty Pickups and Vans, Vocational Vehicles and Tractors with a gross vehicle weight rating higher than 8,500 pounds (3,856 kg) and the model years (MY) 2014-2018.<sup>138</sup> The Phase I fuel standards lead to a significant fuel efficiency increase in the 2011-2017 timeframe.<sup>139</sup> However, it was recognized that the greenhouse gas savings triggered by Phase I would not be enough to achieve the economic and ecological targets, as they were largely offset by a rise in miles driven. Therefore, stricter fuel efficiency targets for the timeframe 2018-2027 were approved in 2014.<sup>140</sup> It is forecasted that these Phase II standards will reduce the fuel consumption significantly. The fuel economy standards for Canada are not presented here, as they are highly aligned with the US standards.<sup>141</sup>

## **Chinese Approach – National Fuel Consumption Standard**

The National Fuel Consumption Standard, which is also labelled Stage II Standard, requires fuel consumption for five categories of new heavy goods vehicles ( $\geq 3.5$  t) to be lower than a fuel consumption limit from 2015 onwards.<sup>142</sup> The five categories are commercial trucks, tractors, coaches, dump trucks, and buses.<sup>143</sup> In addition to different fuel consumption limits in l/100km for the five heavy goods vehicles categories, different limits within each category were defined.<sup>144</sup> Dynamometer testing

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<sup>137</sup> NHTSA (2015), p. 1-1f.

<sup>138</sup> Ibid., p. 1-2

<sup>139</sup> Sharpe, B. (2016), p. 11

<sup>140</sup> NHTSA (2015), p. 1-2f.

<sup>141</sup> Aarnink et al. (2013), p. 34

<sup>142</sup> Ibid., p. 32f.

<sup>143</sup> Ibid.

<sup>144</sup> Ibid., p. 32

and simulation modelling were used to determine the fuel consumption limits.<sup>145</sup> Stricter Phase III standards will likely be introduced between 2019 and 2021.<sup>146</sup>

### **European approach – VECTO**

The European Commission follows a different path and had not introduced CO<sub>2</sub> emissions limits for heavy goods vehicles until 2018. From 2019 onwards, truck manufacturers are obliged to certify and report the CO<sub>2</sub> emissions of all new trucks they want to sell in Europe due to the Certification Regulation and the Monitoring and Reporting Regulation.<sup>147</sup> The underlying idea is that this transparency will increase the competition between truck manufacturers to produce efficient trucks and therefore will increase the uptake of low emission trucks in the market. The simulated CO<sub>2</sub> values are the references for setting CO<sub>2</sub> emission standards for heavy goods vehicles.<sup>148</sup> The Commission had engaged TU Graz to develop the CO<sub>2</sub> simulation tool to estimate the fuel consumption and CO<sub>2</sub> values of heavy goods vehicles. This tool is called VECTO (Vehicle Energy Consumption Calculation TOol) and is based on real-world data from manufacturers on the engine and values for air, transmission and driven axle drag and rolling resistance. Further input data from truck manufacturers are vehicle configuration, weight, transmission and axles ratios, tyre type and size and auxiliary specifications.<sup>149</sup> Different drive cycles, chassis and axle configurations and weight categories are considered to depict the CO<sub>2</sub> values of the real world operations realistically.<sup>150</sup> All the CO<sub>2</sub> regulations, which are already in place worldwide, are truck type specific and are “stratified by vehicle size and purpose”<sup>151</sup> within these truck types. The disadvantage of differentiating limits by duty cycle is that fleet operators could be stimulated to use regional delivery trucks for long-haul transport if their CO<sub>2</sub> emissions limit is significantly lower than for tractor-trailers. Another option to define CO<sub>2</sub> fleet targets is to use a limit curve.<sup>152</sup> The mass dependent limit curve to determine the fleet target value is applied in the car and light-duty vehicle segment and a similar approach could have been applied in the heavy goods vehicles segment

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<sup>145</sup> Aarnink et al. (2013), p. 33

<sup>146</sup> European Commission (2018b), URL see Bibliography

<sup>147</sup> Ibid.

<sup>148</sup> LowCVP (2017), URL see Bibliography

<sup>149</sup> ACEA (2015), p. 31

<sup>150</sup> Ibid., p. 20

<sup>151</sup> Teter. et al. (2017), p. 42

<sup>152</sup> Aarnink et al. (2013), p. 65

as well. According to the regulation for light goods vehicles, the average CO<sub>2</sub> output of the European vehicle fleet may not exceed 175 g/km. Van manufacturers that sell heavier vehicles may exceed this target value. The actual CO<sub>2</sub> emissions limit for each manufacturer is dependent on the average mass of its new sales fleet and is calculated as follows:<sup>153</sup>

$$\text{CO}_2^{\text{lim}}(t) = X + a (M - M_0) \quad ( 1 )$$

M: Mass of the vehicle [kg]

M<sub>0</sub>: Reference mass [1706 kg]

a: Slope of the limit curve [0.093]

X: Average fleet target value [175 gCO<sub>2</sub>/km in 2015 and 147 gCO<sub>2</sub>/km in 2020]

Furthermore, super credits could be used to incentivize the production of zero-emission vehicles. The super credit regulation for the light goods vehicles, which runs out in 2018, allows multiple crediting of vehicles, which do not exceed 50 gCO<sub>2</sub>/km.<sup>154</sup> The fees for exceeding the CO<sub>2</sub> emissions limit by one g/km are €5, rising to €15 for the second g/km and €25 for the third g/km and finally reaching the maximum of €95 for each following g/km.<sup>155</sup> Beginning with the year 2019, the van manufacturers will have to pay €95 for each gram they exceed their specific CO<sub>2</sub> emissions limit.<sup>156</sup>

The European Commission has published a proposal for fuel economy standards for heavy goods vehicles in May 2018.<sup>157</sup> In coherence with other policy regulations like the Renewable Energy Directive, the Fuel Quality Directive, the Clean Vehicles Directive, the Energy Efficiency Directive and the Directive on the deployment of alternative fuels infrastructure (AFID), the CO<sub>2</sub> emission standards will contribute to achieving the GHG emission reduction targets of the European Union. The European

<sup>153</sup> European Environment Agency (2017), p. 11f.

<sup>154</sup> Ibid., p. 10

<sup>155</sup> European Commission (2017b), URL see Bibliography

<sup>156</sup> Ibid.

<sup>157</sup> European Commission (2018a), URL see Bibliography

Commission favours a single manufacturer specific target calculated as a weighted average of targets of vehicle subgroups and accompanied by super-credits for low- and zero emission vehicles over separate targets for subgroups of heavy-duty vehicles. The subgroups capture the impact of truck design and trailer configuration, drive cycle characteristics and payload on the CO<sub>2</sub> emissions output.<sup>158</sup> The CO<sub>2</sub> emissions reduction target will take into account the fleet composition of manufacturers and give them the flexibility to balance more polluting vehicles of one subgroup with cleaner vehicles of another subgroup.<sup>159</sup> A truck is classified as a low emission vehicle and thus eligible for super-credit if its emissions go below the threshold of 350 gCO<sub>2</sub>/km.<sup>160</sup> Zero emission vehicles are counted twice, and low emission vehicles are counted as up to two vehicles depending on the CO<sub>2</sub> emissions output.<sup>161</sup> The super-credit system will be accompanied by a cap that limits the reduction of the average specific emissions of a manufacturer by super-credits to 3 percent, as otherwise the increase of emissions of other drivetrain options could be unintentionally supported.<sup>162</sup> The cap avoids this weakening of the CO<sub>2</sub> standard. There are several possibilities to set a CO<sub>2</sub> standard, ranging from an engine-only CO<sub>2</sub> standard to a whole-vehicle standard.<sup>163</sup> Manufacturers are in favour of the whole-vehicle standard including the trailer and body type and argue that an engine-only standard will not reflect the diversity and complexity of the trucking business.<sup>164</sup> Another advantage is that it does not exclude potential savings from measures like aerodynamic optimization and gives the possibility to install the technologies with the lowest marginal cost of abatement.<sup>165</sup> However, this issue gives rise to the concern that innovations like hybridization, which have the potential to reduce emissions significantly, but are expensive, will be hampered.<sup>166</sup> An engine standard in addition to a whole-vehicle standard would solve that problem.<sup>167</sup> The European Commission is in favour of the whole-vehicle standard that is based on a Tank-to-Wheel approach and that uses the gCO<sub>2</sub>/tkm metric, which reflects the commercial function of the vehicle.<sup>168</sup>

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<sup>158</sup> European Commission (2018a), URL see Bibliography

<sup>159</sup> Ibid.

<sup>160</sup> Ibid.

<sup>161</sup> Ibid.

<sup>162</sup> Ibid.

<sup>163</sup> Aarnink et al. (2013), p. 5

<sup>164</sup> ACEA (2016b), URL see Bibliography

<sup>165</sup> Aarnink et al. (2013), p. 5

<sup>166</sup> Ibid., p. 5

<sup>167</sup> European Commission (2018b), URL see Bibliography

<sup>168</sup> Ibid.

The standards will be put in place in two stages. A CO<sub>2</sub> emissions reduction target of 15% for the year 2025 relative to 2019 levels will be binding for the four most polluting commercial vehicles.<sup>169</sup> These are “(a) rigid lorries with an axle configuration of 4x2 and a technically permissible maximum laden mass exceeding 16 tons; (b) rigid lorries with an axle configuration of 6x2; (c) tractors with an axle configuration of 4x2 and a technically permissible maximum laden mass exceeding 16 tons; (d) and tractors with an axle configuration of 6x2.”<sup>170</sup> Vocational vehicles like garbage trucks and construction lorries are excluded as the CO<sub>2</sub> reduction potential is lower and costlier to utilize than for delivery trucks.<sup>171</sup> The target for 2025 is achievable with cost-effective technologies that are readily available in the market.<sup>172</sup> The aspirational target of 30% CO<sub>2</sub> emissions reduction for the year 2030 will be reviewed in 2022, and the CO<sub>2</sub> regulation will be extended to other commercial vehicles like smaller trucks with a Gross Vehicle Weight Rating less than 16 t.<sup>173</sup> The CO<sub>2</sub> reduction targets are given as percentage improvements, as the definition of absolute target values requires certified CO<sub>2</sub> emissions data, which will be available from 2019 onwards.<sup>174</sup>

Furthermore, the European Commission is considering the possibility of banking and borrowing CO<sub>2</sub> credits across compliance years.<sup>175</sup> The excess emission premium is €6800 per gCO<sub>2</sub>/tkm, which is equivalent to €570 per gCO<sub>2</sub>/km for a truck with an average payload of 12 tonnes.<sup>176</sup>

Another regulatory measure to reduce CO<sub>2</sub> emissions in freight transport could be the inclusion of the transport sector into the European Emission Trading System (EU-ETS). One design option of such a cap-and-trade-system is the setting of CO<sub>2</sub> emissions limits for primary energy producers. In this case, the development of a complex tool like VECTO would not have been necessary. But there are serious concerns about the effectiveness of such a system, like high administrative effort for emissions monitoring<sup>177</sup> and a dramatic increase in fuel prices that would primarily hit

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<sup>169</sup> European Commission (2018a), URL see Bibliography

<sup>170</sup> Ibid.

<sup>171</sup> Ibid.

<sup>172</sup> Ibid.

<sup>173</sup> Ibid.

<sup>174</sup> European Commission (2018b), URL see Bibliography

<sup>175</sup> European Commission (2018a), URL see Bibliography

<sup>176</sup> European Commission (2018b), URL see Bibliography

<sup>177</sup> NHTSA (2010), p. 43f.

smaller trucking companies.<sup>178</sup> A downstream approach that allows fleet operators to trade emission allowances would result in high transaction costs due to the high number of transaction partners.<sup>179</sup> Imposing a higher tax on diesel fuel is a further regulatory measure that the government could take to reduce the CO<sub>2</sub> emissions of road freight transport. In contrast to a CO<sub>2</sub> standard, which only applies to new vehicles, fuel taxation addresses all trucks on the road.<sup>180</sup> The idea behind fuel taxation is to encourage fleet operators to use fuel-efficient trucks and to drive more fuel-efficient. But the effectiveness of fuel taxation depends on the fuel price sensitivity of truck operators.<sup>181</sup> However, as will be explained in another chapter, this sensitivity is low for urban transport. Long before the European Commission published the strategy for low-emission mobility and initiated the development of the simulation tool VECTO, the UK had already taken significant steps to make its economy carbon neutral in the long term. The UK has committed itself to tackle climate change by adopting the Climate Change Act 2008, which requires that the UK cuts its greenhouse gas emissions by at least 80 percent by 2050 compared to 1990 levels.<sup>182</sup> This national reduction goal goes even further as the Renewables Energy Directive of the EU and guarantees that Brexit will not mean an end to the environmental goals of the UK.<sup>183</sup> The member states of the EU have extended the Renewable Energy Directive to 2030 and increased the renewable energy target.<sup>184</sup> Accordingly, 27 percent of the final energy consumed across the EU must come from renewables by 2030.<sup>185</sup> In 2014, the heavy goods vehicles in the United Kingdom were responsible for 16 percent of the greenhouse gas emissions from the transport sector, which had a share of nearly a quarter of total United Kingdom greenhouse gas output.<sup>186</sup> According to the Freight Carbon Review 2017 from the Department of Transport, there are five main blocks of measures, which could potentially bring the UK closer to its 2050 carbon reduction target:

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<sup>178</sup> Patton, O. (2009), URL see Bibliography

<sup>179</sup> Aarnink et al. (2013), p. 26

<sup>180</sup> Ibid., p. 22

<sup>181</sup> Ibid., p. 23

<sup>182</sup> The National Archives (2008), p. 1

<sup>183</sup> Gosden, E. (2017), URL see Bibliography

<sup>184</sup> European Commission (2017c), URL see Bibliography

<sup>185</sup> Ibid.

<sup>186</sup> Department for Transport (2017a), p. 16f.

- “Improving fuel economy through efficient driving and in-cab driver monitoring technologies.
- Optimising fleet design through retrofit technologies and improved engine efficiency.
- Reducing road miles through modal shift, longer-semi trailers and further industry collaboration.
- Reducing emissions through wider use of alternative fuels.
- Shifting the focus to future, more radical, solutions such as electric trucks, e-highways and hydrogen fuel cell technologies.”<sup>187</sup>

The first, the third and the fourth strategy to reduce the carbon content of transport are not part of the investigation. The focus of the dissertation will be mainly on the last point, namely the uptake of electric trucks in the market. However, fuel and CO<sub>2</sub> saving measures like retrofit technologies and engine efficiency improvement will be integrated into the diffusion model.

### 2.2.2 T-CHARGE AND ULTRA LOW EMISSION ZONE: TACKLING POOR AIR QUALITY

There exist several measures, which can be taken to improve air quality in urban areas. Examples for these measures are low emission zones (LEZs) with a ban on driving or a charge of vehicles with high emissions, a ban of transit traffic through the city or from defined routes with the highest pollution levels, a tightening of speed limits, the optimization of traffic lights steering to improve traffic flow, days with a ban of driving on vehicles with even/uneven license tags and the improvement of local public transport.<sup>188</sup> The British Government has placed the improvement of air quality in British cities at the forefront of its environmental agenda. However, the reason for this is not only environmental, but also financial. Air pollution holds back economic development by putting a burden on companies and the health budget due to a rise in the number of disease cases it causes. Furthermore, the exceeding of limits for major pollutants like nitrogen dioxide and particulate matter, which are binding for the UK

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<sup>187</sup> Department for Transport (2017a), p. 8

<sup>188</sup> Daimler AG

due to the 2008 Ambient Air Quality Directive (2008/50/EC), results in significant penalties for city administrations.<sup>189</sup> The transport sector is by far the greatest contributor to air pollution, which is a mixture of different pollutants like nitrogen oxides (NO<sub>x</sub>), particulate matter (PM), sulphur dioxide (SO<sub>2</sub>), non-methane volatile organic compounds (NMVOCs) and ammonia (NH<sub>3</sub>).<sup>190</sup> These pollutants have severe consequences, ranging from cancer (PM) and risk for the human respiratory system to acid rain (NO<sub>x</sub>).<sup>191</sup> The Greater London urban area is struggling with the highest nitrogen dioxide (NO<sub>2</sub>) levels in the UK.<sup>192</sup> The hidden potential of pollutant emission savings in London's commercial transport sector becomes clear if it is considered that commercial vehicles based in London make 280,000 operations every weekday, which corresponds to eight million miles.<sup>193</sup> The British government has published a plan aiming to improve air quality in London and other British towns and cities by tackling nitrogen dioxide to exploit this full potential.<sup>194</sup> The measures for London include, among others, the introduction of a Toxicity Surcharge ('T-Charge') from 23 October 2017 on and the implementation of an Ultra Low Emission Zone (ULEZ) in April 2019.<sup>195</sup> The vehicle operator has to pay a daily emission surcharge of £10 (T-Charge) in addition to the congestion charge of £11.50 for driving into the Congestion Charge Zone from 7 am to 6 pm, if the heavy goods vehicle exceeding 3.5 t does not meet the Euro 4 emission standard.<sup>196</sup> The T-Charge will be automatically replaced by the introduction of the world's first Ultra Low Emission Zone (ULEZ) (see Figure 8), which also covers the Congestion Charge Zone (CCZ) but sets higher emission standards and applies 24 hours a day and 365 days a year.<sup>197</sup> From October 2020 onwards, the Ultra Low Emission Zone will include heavy goods vehicles, which would then have to pay a daily charge of £100 for entering Greater London, if their emission standard is below Euro 6 and £300 if their emission standard is below Euro 3.<sup>198; 199</sup> This Ultra Low Emission Zone can be seen as the first step towards a Zero Emission Zone. Furthermore, the Mayor of London is cooperating with Transport for London (TfL) to

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<sup>189</sup> European Commission (2008), p. L 152/12

<sup>190</sup> Defra (2017a), p. 44f.

<sup>191</sup> Ibid., p. 3

<sup>192</sup> Ibid., p. 31

<sup>193</sup> edie.net (2017), URL see Bibliography

<sup>194</sup> Defra (2017a), p. 12

<sup>195</sup> Ibid., p. 32

<sup>196</sup> Transport for London (2017a), URL see Bibliography

<sup>197</sup> Ibid.

<sup>198</sup> Ibid.

<sup>199</sup> Pink, H. (2018), URL see Bibliography

make the public and commercial transport fleets in London greener. For example, Transport for London may replace its double deck diesel buses only with a hybrid, electric or hydrogen buses from 2018 onwards.<sup>200</sup> Such public procurement rules are an effective way to support the uptake of emission-free vehicles. To reduce pollutant emissions of freight transport, Transport for London has set up the LoCITY initiative. LoCITY brings together different stakeholders of freight transport in working groups and aims to bolster the diffusion of low emission commercial vehicles and refuelling and charging infrastructure in London and to prepare the freight sector for the introduction of the Ultra Low Emission Zone in 2020.<sup>201</sup>

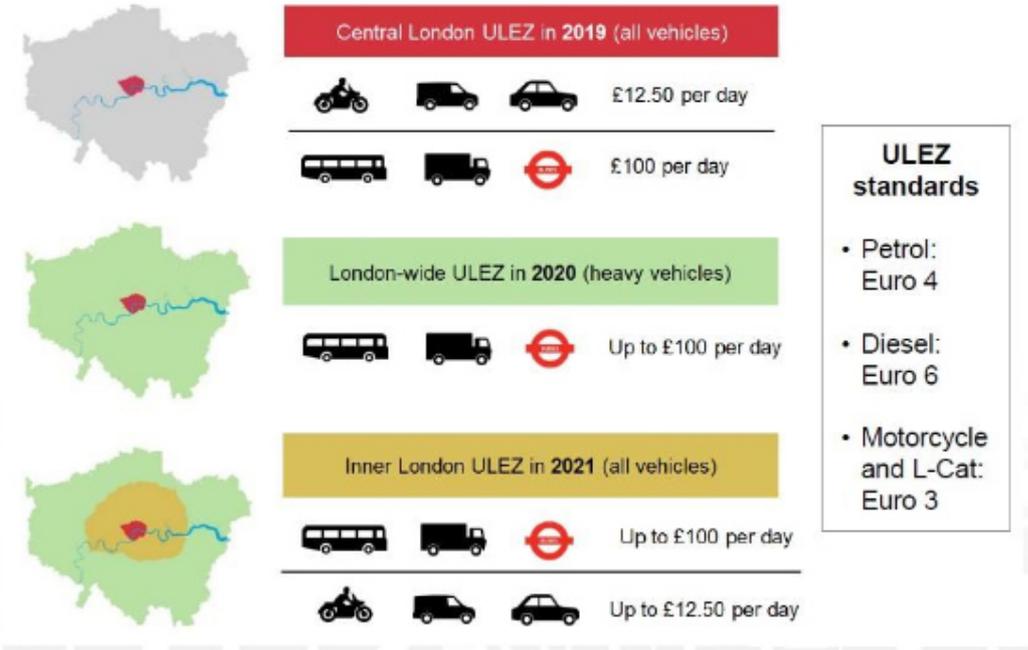


Figure 8 Ultra Low Emission Zone in London<sup>202</sup>

### 2.3 DIESEL TRUCK EFFICIENCY AND TRUCK ELECTRIFICATION

Manufacturers need to respond to these increasingly stricter regulations with the introduction of more efficient diesel trucks and electric trucks that do produce fewer tailpipe emissions or can drive completely emission-free. The following chapters list

<sup>200</sup> London.gov.uk (2017), URL see Bibliography  
<sup>201</sup> LoCITY (2017a), URL see Bibliography  
<sup>202</sup> Lord, O. (2017), p. 24

the technical options that can pave the way to a greener freight transport and help manufacturers to meet the fuel economy standard that is going to be introduced in the EU in the next decade. The chapter concludes with an overview of trucks with electric drivetrains that were introduced into the market.

### 2.3.1 FUEL SAVING MEASURES

There are more stringent nitrogen oxides (NO<sub>x</sub>) and particulate matter (PM) limits for heavy goods vehicles since the introduction of the Euro 6 standard in January 2013.<sup>203; 204</sup> The standards for the triad markets are on comparable levels, whereas China follows them with a delay of a couple of years. The demanding and rigorous standards for nitrogen oxides (NO<sub>x</sub>) and particulate matter (PM) are indications that the regulatory focus will shift towards greenhouse gases in the coming decade. In 2008, truck manufacturers committed themselves to contribute to the greening of the transport sector. Their 'Vision 20-20' strategy targeted a greenhouse gas reduction of 20 percent compared to 2005 levels, what corresponds to a fuel consumption reduction of 1.3 percent per year.<sup>205</sup> There are generally two different strategies to reduce emissions from combustion processes. One strategy is to limit the formation of emissions in the cylinder by "adjusting the temperature and air/fuel balance within the engine, using improvements to fuel injection and air handling and employing exhaust gas recirculation".<sup>206</sup> The exhaust gas recirculation (EGR) system feeds a portion of the exhaust gas back to the cylinder to lower the peak combustion temperature that is responsible for the formation of nitrogen oxides (NO<sub>x</sub>).<sup>207</sup> The second strategy provides for the elimination of emissions in the exhaust aftertreatment system with selective catalytic reduction (SCR) for nitrogen oxides (NO<sub>x</sub>) and diesel particulate filter for particulate matter (PM).<sup>208</sup> The selective catalytic reduction system works with a chemical known as Ad-Blue. Manufacturers were able to fulfil Euro 5 standards with the exhaust gas recirculation but needed to combine selective catalytic reduction,

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<sup>203</sup> Sharpe et al. (2011), p. 9

<sup>204</sup> Ibid., p. 10

<sup>205</sup> ACEA (2014), URL see Bibliography

<sup>206</sup> Posada et al. (2016), p. iv

<sup>207</sup> Ibid.

<sup>208</sup> Ibid.

exhaust gas recirculation and diesel particulate filter to meet Euro 6 standards. However, technological enhancements, like the engine of Scania, have shown that it is possible and more fuel efficient to meet Euro 6 standard only by the selective catalytic reduction.<sup>209</sup> The fuel efficiency of the diesel engine with an “SCR only” system could increase by one percentage point.<sup>210</sup> Further measures which have the potential to contribute to fuel consumption benefits are the reduction of frictional losses in the engine through the deployment of low-viscosity oil and the reduction of auxiliary parasitic losses through the use of a variable oil pump and a variable water pump.<sup>211</sup> Low-viscosity oil can also be used to reduce the frictional losses in the gearbox and axle drives.<sup>212</sup> Additional fuel savings can be achieved through dry sump lubrication with a variable oil pump instead of wet sump lubrication, thereby reducing the churning losses.<sup>213</sup> A reduction in fuel consumption with a good benefit-cost ratio is possible with the replacement of conventional tyres with low rolling resistance tyres, which consist of a special material and have different tread patterns.<sup>214</sup> Furthermore, weight and consequently fuel can be saved by replacing a pair of tyres with single wider tyres.<sup>215</sup> Lightweight materials can lead to further weight reductions and fuel savings. Although the weight of rigid trucks increased due to the introduction of the Euro 6 regulation, it is expected that manufacturers will increasingly offer rigid trucks variants with lower kerb weight<sup>216</sup> and customers will demand trucks that save weight and thus fuel.<sup>217</sup> Aerodynamic measures considered for the urban delivery duty cycle are partial fairing and a short boat tail to prevent the formation of air vortices.<sup>218</sup> In addition to that, rearview cameras with a streamlined shape could replace side mirrors, thereby reducing the aerodynamic drag.<sup>219</sup> Together, all of these aerodynamic measures lead to a fuel consumption reduction of 2.4 percentage points.<sup>220</sup> By increasing the efficiency of auxiliaries like the compressor, the power steering pump and lights, additional fuel savings of 1.6 percent can be achieved.<sup>221</sup> The fuel economy gain of an

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<sup>209</sup> Björkegren, J and Åslund, Ö. (2014), URL see Bibliography

<sup>210</sup> Dünnebeil et al. (2015), p. 161

<sup>211</sup> Ibid.

<sup>212</sup> Ibid., p. 162

<sup>213</sup> Ibid.

<sup>214</sup> Norris, J. and Escher, G. (2017), p. 55

<sup>215</sup> Dünnebeil et al. (2015), p. 163

<sup>216</sup> Hill et al. (2015), p. 23f.

<sup>217</sup> Klemick et.al. (2015), p. 164

<sup>218</sup> Dünnebeil et al. (2015), p. 163

<sup>219</sup> Ibid.

<sup>220</sup> Ibid., p. 176

<sup>221</sup> Ibid., p. 177

engine start-stop system to reduce the idle times is assumed to be 2.2 percentage points for the urban delivery truck.<sup>222</sup> However, these fuel-saving measures alone will not suffice to reach the challenging environmental targets. A significant reduction in CO<sub>2</sub> necessitates the market uptake of trucks with partly and fully electric drivetrains.

### 2.3.2 DRIVETRAIN TECHNOLOGIES

The graph below shows drivetrain technologies for trucks, which are sorted by their degree of electrification in ascending order from left to right (see Figure 9). As can be seen from the graph, the electrification of the truck requires a battery, and its size rises with increasing electrification.

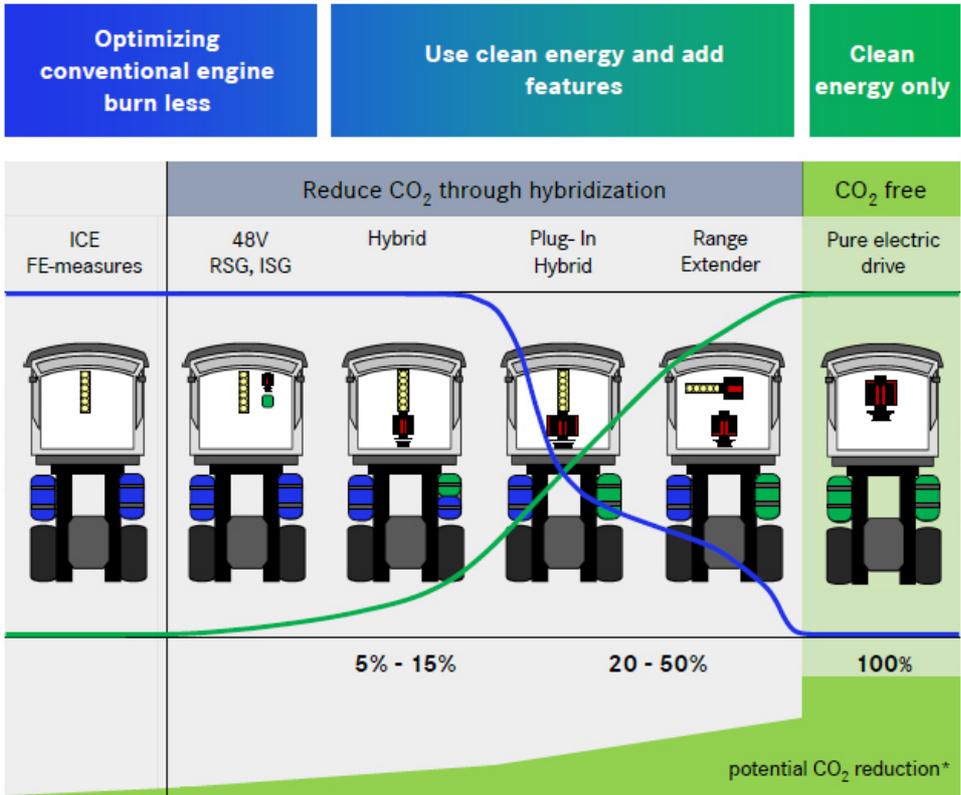


Figure 9 Drivetrain technologies<sup>223</sup>

<sup>222</sup> Dünnebeil et al. (2015), p. 177

<sup>223</sup> Daimler AG

Whereas the hybrid, plug-in hybrid, and range-extended electric truck have two different energy storages, the battery electric truck only uses a battery as the source of propulsion. The graph does not distinguish between a battery electric truck and a fuel cell electric truck, as both of them are driven solely by an electric motor. However, they differ in the energy storage system. Whereas a battery electric truck uses a battery to store the energy needed to power the truck, the fuel cell electric truck uses onboard hydrogen storage. The hydrogen loaded on board is converted to electricity during the trip. Both the battery electric truck and the fuel cell electric truck have the potential to be CO<sub>2</sub> free if they use renewably-produced energy. In the following, the different electric drivetrain technologies for trucks are explained in greater detail.

### **Mild Hybrid Truck**

Strictly speaking, a mild hybrid truck should not be classified as an electric truck, as it cannot drive purely electrical. Instead, it is a common diesel truck which is fitted with a flywheel or other type of kinetic energy recovery system (KERS) that recovers energy from braking.<sup>224</sup> This makes the mild hybrid technology ideally suited for duty cycles with a lot of stop-and-go traffic. The recovered energy is used by the electric motor to back the internal combustion engine in the acceleration phase.<sup>225</sup> This type of vehicle typically does not possess a battery.<sup>226</sup>

### **Hybrid Electric Truck**

Hybrid electric trucks are divided into two categories, namely serial hybrid electric trucks and parallel hybrid electric trucks. The internal combustion engine in serial hybrid electric trucks is not mechanically connected with the drive axle. The drive power comes solely from an electric motor, whereas the parallel hybrid electric truck can be powered by the internal combustion engine and the electric motor separately or by both of them. The system allows energy recovery from braking and enables emission-free driving for a few kilometres.

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<sup>224</sup> Department for Transport (2017a), p. 75

<sup>225</sup> Ibid.

<sup>226</sup> Ibid.

### **Plug-In Hybrid Electric Truck**

The difference between hybrid and plug-in hybrid electric trucks is that the battery of hybrid electric trucks can only be charged by recuperation, whereas the battery of plug-in hybrid electric trucks can be charged from the standard electrical wall socket. The battery is larger compared with the ones of the mild-hybrid and hybrid electric trucks and thus allows for driving a longer distance purely electric.

### **Range Extended Electric Truck**

The range-extended electric truck is a series hybrid electric truck, which is propelled by an electric motor. It overcomes the limitations of the insufficient range of electric trucks by using a diesel or gas engine or a fuel cell as the source of power. By this, the engine or the fuel cell charges the depleted battery and extends the range of the truck.<sup>227</sup> When parked, the electrical grid can be used for charging. The truck normally operates in a charge-depleting mode, which means that the engine/fuel cell is started once the battery is fully depleted.<sup>228</sup>

### **Battery Electric Truck**

The range of the battery electric truck cannot be extended during driving, as it solely uses the battery as the source of propulsion and therefore can only be used again after being charged at a charging station. If combined with innovative charging solutions like overhead catenary wire charging or inductive charging, the battery electric truck can drive longer distances without the need to stop for charging. These options are not considered further, as these options are more suitable for long-haul transport and the focus of the dissertation lies on urban delivery. The driving range of battery electric trucks depends on the size of the battery, which is limited due to truck weight and space considerations. Although the battery electric truck is emission-free on a Tank-to-Wheel (TTW) basis, the production of electricity and the manufacturing of the vehicle and batteries generate pollutants and greenhouse gases. Only the decarbonization of the electricity grid by an upscale of renewable energies will contribute to a significant reduction of emissions. The battery technology is considered

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<sup>227</sup> CALSTART (2013), p. 23

<sup>228</sup> Ibid., p. 24

the most important factor regarding the performance and cost of the battery electric truck. There are different battery types existent on the market like lead acid, nickel metal hydride and lithium-ion which can be used for automotive applications.<sup>229</sup> These battery types can be assessed regarding their appropriateness for automotive applications according to the variables energy/weight ratio, energy/volume ratio, power to weight ratio, battery lifetime, charging cycles and charging time.<sup>230</sup> Technological readiness for automotive applications of the batteries is another distinguishing factor, as the battery might be promising regarding energy density like the lithium-air or lithium-sulfur batteries for example, but technological bottlenecks still prohibit their use in commercial applications.<sup>231; 232</sup>

The energy/weight ratio, also known as the energy density of the battery, is a critical factor for the battery electric truck, as it determines the driving range that is possible with a given battery capacity. The electric driving range of battery and plug-in hybrid electric trucks is defined as follows:<sup>233</sup>

$$D_{e, i} = \frac{d_{bat} * m_{bat} * DoD_i}{Q_i^{el}} \quad ( 2 )$$

$D_{e, i}$ : Electric driving range of electric truck type i [km]

$d_{bat}$ : Energy density of battery [kWh/kg]

$m_{bat}$ : Mass of the battery [kg]

$DoD_i$ : Depth of Discharge for truck type i [-]

$Q_i^{el}$ : Energy consumption of truck type i [kWh/km]

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<sup>229</sup> Daimler AG

<sup>230</sup> den Boer et al. (2013), p. 21

<sup>231</sup> Ibid., p. 23f.

<sup>232</sup> Thielmann et al. (2013), p. 24

<sup>233</sup> Plötz et al., p. 165

The following Table 4 lists data needed to calculate the driving range of a plug-in hybrid and battery electric truck.

	PHEV	BEV
Battery weight [kg]	236	830
Energy density [kWh/kg]	0.11	
Nominal energy capacity [kWh]	26	91.3
Depth of Discharge factor for usable capacity [-]	0.7	0.9
Usable energy capacity [kWh]	18.2	82.17
Energy consumption [kWh/km]	0.62	0.62
Maximum full-electric driving range [km]	29.35	133

Table 4 Plug-in hybrid electric truck and battery electric truck specific data for the calculation of electric driving range<sup>234</sup>

The nominal battery energy capacity is a factor of battery weight and energy density of the battery cells. The energy capacity determines the amount of energy that can be extracted for propulsion. One has to distinguish between the nominal capacity and the usable capacity of the battery, which depends on the depth of discharge factor. The depth of discharge is defined as “percentage of battery capacity that has been discharged expressed as a percentage of maximum capacity.”<sup>235</sup> The battery’s rest capacity is built in “to avoid overheating and excessive discharge.”<sup>236</sup>

The range of electric trucks can be extended by increasing the energy density of the battery and reducing the electricity consumption of the electric truck. At present, state of the art in battery technology for the automotive industry is the lithium-ion battery with an energy density of around 110 Wh/kg on a system level.<sup>237</sup> Experts argue that energy densities of around 315 Wh/kg are possible in the future, thus enabling a much higher electric driving range than currently possible.<sup>238</sup> It has to be pointed out that there are additional factors that affect the electric driving range but are not included in

<sup>234</sup> Daimler AG

<sup>235</sup> MIT Electric Vehicle Team (2008), p. 2

<sup>236</sup> Electrification Coalition (2010), p. 79

<sup>237</sup> Thielmann et al. (2013), p. 4

<sup>238</sup> Ibid., p. 4

equation ( 2 ). Examples of this are extremely hot or cold weather conditions, high road's gradient, and the style of driving.<sup>239</sup>

The cheapest way to charge an electric truck is by plugging it into a standard wall box with a charging power of about 3.7 kW. The total cost for a wall box including installation is €1050.<sup>240</sup> But the charging time of an electric truck with a battery capacity of 91.3 kWh would be more than 24 hours. If using the truck in a two-shift operation with 8 hours per shift, the charging time of the battery electric truck must be less than 8 hours. This is possible with a charger that has a charging power of 22 kW. In this case, the charging time is reduced to approximately 4 hours. The total cost of a fast charging point is around €10,000.<sup>241</sup> Even lower charging times between 30 minutes and 2 hours can be achieved by using rapid chargers with a charging power between 50 and up to 150 kW. The total cost for rapid charging points ranges between €35,000 and €90,000.<sup>242</sup> LowCVP states that a 50 kW charging point costs between £38,000 and £45,000.<sup>243</sup> These options are interesting for truck operators, which have sufficient time slots to charge up the vehicle during loading and unloading for example.<sup>244</sup> As delivery trucks return to the depot and can be charged overnight, chargers with a charging power of 22 kW will be sufficient in most cases.<sup>245</sup> Interviews with commercial vehicle operators in London in 2012 have shown that there was hardly any demand for public charging points at that time, as operators deployed electric vehicles in duty cycles for which the driving range of electric trucks was sufficient so that a commercial electric vehicle could be recharged after returning to the depot.<sup>246</sup> Nevertheless, the study authors recommended building up fast and rapid charging points for commercial vehicles.<sup>247</sup> And indeed, Transport for London aims to establish 300 rapid charging points in London by 2020 in the context of the Rapid Charging Infrastructure Project and asked fleet operators to suggest their locations in the city.<sup>248</sup> The majority of transport companies will still charge the vehicle at the depot, as it is not guaranteed that the charging point is free to use in case of a depleted battery, resulting in unproductive waiting times and an increase in transport

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<sup>239</sup> Margaritis et al. (2015), p. 2

<sup>240</sup> Daimler AG

<sup>241</sup> Ibid.

<sup>242</sup> Ibid.

<sup>243</sup> Cluzel, C. and Hope-Morley, A. (2015a), p. 18

<sup>244</sup> Worthy et al. (2015), p. 4

<sup>245</sup> Naberezhnykh et al. (2012), p. 26

<sup>246</sup> Ibid., p. 32

<sup>247</sup> Ibid., p. 28f.

<sup>248</sup> Transport for London (2017b), p. 3f.

costs.<sup>249</sup> However, a study of Transport for London has found out that depot charging will not be enough to electrify all commercial vehicles in urban freight transport, as some drivers park the vehicles at home overnight between shifts, where charging possibilities might not be existent.<sup>250</sup> In addition to that, some truck operators might not have fixed tours, but variable tours<sup>251</sup> or might not have the financial resources to invest in charging points at the depot.<sup>252</sup>

For these reasons alone, the installation of on-street rapid charging points in residential and public areas becomes necessary. In addition to that, operators of larger fleets might reach their limit of depot charging point installation and might want to use public charging points as additional opportunity rapid charging.<sup>253</sup> For modelling purposes, it is thus assumed that only rapid chargers that can be used during shorter breaks come into question for public charging. According to the definition of the reference cycle for urban delivery by the VECTO Model, trucks stop 25 times per day in total with 593 seconds per stop.<sup>254</sup> These timeslots are sufficient to recharge the battery with rapid chargers fully. The challenge with battery charging lies in establishing a world standard for the huge variety of chargers.<sup>255</sup>

## **Fuel Cell Electric Truck**

The fuel cell electric truck guarantees emission-free driving like the battery electric truck, whereas the CO<sub>2</sub> saving potential on a Well-to-Wheel basis depends on the hydrogen production path. Fuel cells are devices in which electricity is produced through a reaction of hydrogen and air. The only by-products leaving the tailpipe are water and heat. Compared with diesel engines, the fuel cell system is more efficient as it can use 50 percent of the energy content of hydrogen.<sup>256</sup> Unlike battery electric trucks, trucks propelled by a fuel cell achieve sufficient ranges of hundreds of kilometres with one tank filling. But in the case of urban freight transport, cost considerations make it necessary to scale the hydrogen tank to offer a range that is

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<sup>249</sup> Baster et al. (2014), p. 35

<sup>250</sup> Worthy et al. (2015), p. 5

<sup>251</sup> Nesterova, N. and Quak, H. (2015), p. 43

<sup>252</sup> Naberezhnykh et al. (2012), p. 31

<sup>253</sup> Worthy et al. (2015), p. 14

<sup>254</sup> Norris, J. and Escher, G. (2017), p. 26

<sup>255</sup> Margaritis et al. (2015), p. 6

<sup>256</sup> U.S. Department of Energy (2013), p. 11

sufficient for urban freight operations. The electric driving range of a fuel cell electric truck is calculated as follows:

$$D_{e,FCEV} = \frac{m_{hyd} * 33.33 \frac{kWh}{kg H_2}}{Q_{FCEV}^{el}} \quad ( 3 )$$

$D_{e,FCEV}$ : Electric driving range of a fuel cell electric truck [km]

$m_{hyd}$ : Mass of hydrogen in the tank [kg]

$Q_{FCEV}^{el}$ : Energy consumption of a fuel cell electric truck [kWh/km]

Table 5 lists data needed to calculate the driving range of fuel cell electric trucks.

	FCEV
Mass of hydrogen in the tank [kg]	7.6
Nominal energy capacity [kWh]	253.3
Energy consumption [kWh/km]	1.9
Maximum full-electric driving range [km]	133

Table 5 Fuel cell electric truck specific data for the calculation of electric driving range<sup>257</sup>

The conversion factor of 33.33 kWh per kg hydrogen (H<sub>2</sub>) is used to calculate the electric driving range.<sup>258</sup> What fuel cell and electric battery drivetrains have in common is that they avoid losses associated with diesel engines like friction, thermal and combustion losses.<sup>259</sup> Nevertheless, the efficiency of a fuel cell drivetrain is lower compared to the battery-electric drivetrain, as the hydrogen has to be converted into electricity before it can be used for propulsion.<sup>260</sup> The hydrogen fuel is typically carried in the gaseous or liquid form in specially designed storage tanks on board.<sup>261</sup> In contrast to battery electric trucks, the refuelling of fuel cell electric trucks takes only a

<sup>257</sup> Daimler AG

<sup>258</sup> Linde Gas, p. 2

<sup>259</sup> den Boer et al. (2013), p. 8

<sup>260</sup> Ibid.

<sup>261</sup> Ibid., p. 51f.

few minutes, and the driving range is much higher.<sup>262</sup> The battery in a fuel cell electric truck recovers energy from braking and acts as an assistant in the acceleration phase.<sup>263</sup> The fuel cell electric truck is heavier than the diesel truck, which is attributed to the fuel cell system, hydrogen tanks, and batteries. The biggest challenges facing the diffusion of fuel cell electric trucks are the high fuel cell costs and thus the high purchase price and the lack of hydrogen refuelling infrastructure. However, there are several other problems, which need to be solved to make fuel cell trucks competitive. One of these problems is that hydrogen heats up and leads to an increase in tank pressure when the vehicle is parked for a longer period.<sup>264</sup> As a result of that, hydrogen has to be released from the tank, leading to a significant fuel loss.<sup>265</sup> In spite of these weaknesses, the delivery company UPS has noticed the advantages of fuel cell electric trucks and decided to test 17 of them by the end of the year 2018.<sup>266</sup> The major hydrogen production technology pathways are Distributed Natural Gas Reforming, Bio-Derived Liquids Reforming, Coal and Biomass Gasification, Water Electrolysis, Thermochemical Production, Photoelectrochemical Production, and Biological Production.<sup>267</sup> The hydrogen can be produced on-site or can be transported to the station with trucks in gaseous or liquid form or via pipelines.<sup>268</sup> Hydrogen refuelling stations are much more costly than electric charging points. A comprehensive introduction of hydrogen refuelling stations will, therefore, require the cooperation of different stakeholders like automobile manufacturers, fuel suppliers, and governmental authorities. A good example for this is the project H<sub>2</sub> Mobility, which brings together Daimler and the fuel suppliers Air Liquide, Linde, OMV, Shell and TOTAL and aims to establish 400 hydrogen refuelling stations.<sup>269</sup> A similar project called UK H<sub>2</sub> mobility was launched in the UK with the aim to achieve full national coverage with 1150 stations by 2030.<sup>270</sup> In the literature, the weight increase of electric trucks is mentioned as a barrier to adoption. However, Daimler calculated that after removing diesel truck components like the diesel engine, radiator, gearbox, prop shaft, differential, after treatment, exhaust system and Ad-Blue tank, the weight increase for the 26 t Urban eTruck is only 700 kg. Nevertheless, it has to be mentioned that

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<sup>262</sup> den Boer et al. (2013), p. 51

<sup>263</sup> Ibid., p. 49

<sup>264</sup> CALSTART (2013), p. 34

<sup>265</sup> Ibid.

<sup>266</sup> O'Dell, J. (2017), URL see Bibliography

<sup>267</sup> FreedomCAR and Fuel Partnership (2009), p. xiv

<sup>268</sup> Körner, A. (2015), p. 16

<sup>269</sup> H<sub>2</sub> Mobility, URL see Bibliography

<sup>270</sup> UK H<sub>2</sub> Mobility, URL see Bibliography

Daimler took into account the European Commission’s proposal to allow electric trucks an additional tonne payload.<sup>271</sup> Otherwise, the payload penalty would be 1.7 tonnes.<sup>272</sup> This extra weight allowance is only eligible for trucks which are used in international freight transport, but the Department for Transport thinks of applying this policy for national transport as well.<sup>273</sup> The following Table 6 presents an overview of the components, which are not needed for electric trucks and are therefore removed. Furthermore, it shows, which components are added in comparison to the diesel truck.

	PHEV	BEV	FCEV
Engine	0	-534	-534
Engine cooling system and air intake	0	-41	-41
Tank system	0	-171	-171
Transmission	0	-155	-155
Exhaust gas system	0	-70	-70
Battery system	236	830	80
E-machine	55	65	65
Additional components	129	271	219
Fuel cell system (incl. fluid)	0	0	267
Hydrogen (H <sub>2</sub> ) storage system	0	0	129
Additional fuel cell components	0	0	23
<b>Total</b>	<b>420</b>	<b>197</b>	<b>-190</b>

Table 6 Weight change of 12 t electric truck in kg<sup>274</sup>

The highest weight increase is attributed to the battery system. The plug-in hybrid electric truck is the truck type with the highest weight increase, as it has two drivetrain technologies. Surprisingly, the fuel cell electric truck is slightly lighter than its diesel counterpart. The reason for that is that the hydrogen tank is scaled to offer a range of 133 km. A higher range is coupled with a bigger tank and thus a higher weight. A range of 1,000 km would require a hydrogen tank with a weight of 1,733 kg, thus leading to a total weight increase of about 1,111 kg. The same holds for battery electric trucks, which would need a battery system with a weight of 1,733 kg to drive 227 km purely electric. It is obvious that manufacturers will offer trucks with right-sized

<sup>271</sup> EUR-Lex (2015), p. L 115/2

<sup>272</sup> Norwell, I. (2016), URL see Bibliography

<sup>273</sup> Pink, H. (2016b), URL see Bibliography

<sup>274</sup> Daimler AG

batteries which fit the mileage needs of truck operators, as this limits the upfront cost of vehicles and the weight increase.<sup>275</sup> The kerb weight of a 12 t diesel truck is 7,750 kg and the maximum payload is 4,150 kg.<sup>276</sup> In the light of these data and the fact that urban delivery trucks are typically not fully loaded, the payload penalty from above seems to be acceptable.<sup>277; 278</sup>

A comprehensive list of medium and heavy-duty zero-emission vehicles in development or production can be found in the paper “Transitioning to Zero-Emission Heavy-Duty Freight Vehicles.”<sup>279</sup> Another list with detailed technical specifications of electric trucks like payload, battery capacity, electric driving range, charging duration or power of the electric motor can be found on the webpage of eurotransport.de.<sup>280</sup> In the following, some of the trucks with a partial or full degree of electrification, that have been introduced into the market throughout the last years, are presented:

### **BYD T7**

The battery of the class 6 T7 provides a range of 124 miles, and BYD claims that the battery will still have 80 percent of its capacity after 5,000 charging cycles if it is charged every day.<sup>281</sup> The fully electric T7 can be integrated into a Vehicle-to-Grid (V2G) system.<sup>282</sup> Thus, in case of a power outage, the T7 can provide the required energy. According to BYD, the truck saves \$8,200 on fuel per year when it is driven 100 km daily and six days per week and annual maintenance savings amount to \$4,600.<sup>283</sup>

### **DAF LF Diesel Electric Hybrid and DAF LF Electric Innovation Truck**

DAF presented the 19 tonnes DAF LF Electric Innovation Truck at the International Automobile Exhibition (IAA) in 2018. The 19 t distribution comes with a 250 kW electric

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<sup>275</sup> Electrification Coalition (2010), p. 110

<sup>276</sup> Norris, J. and Escher, G. (2017), p. 15

<sup>277</sup> Gota, S. and Wang, B. (2017), p. 20

<sup>278</sup> ACEA (2010), p. 7

<sup>279</sup> Moulak et. al (2017), p. 45f.

<sup>280</sup> Hoffmann, J. (2018), p. 12ff.

<sup>281</sup> BYD, p. 2

<sup>282</sup> Ibid.

<sup>283</sup> Ibid.

motor and a lithium-ion battery capacity of up to 222 kWh, allowing pure electric driving of about 222 kilometres at full load, which will be enough for most operations in urban zones.<sup>284</sup> DAF offers customization of battery pack sizes depending on the range requirements of customers.<sup>285</sup>

### **HINO 195h Hybrid**

HINO Trucks belongs to Toyota, which already is a forerunner in hybrid technology in the passenger vehicle market. Toyota wants to repeat this success in the commercial vehicle market. The HINO 195h targets the North-American Market, is equipped with a nickel-metal hydride battery and is 25 percent more fuel efficient than its diesel version.<sup>286</sup>

### **Iveco Eurocargo Hybrid**

Iveco praises its Eurocargo with parallel hybrid traction, which is designed for the collection and delivery of goods in cities and is 200 kg heavier than its diesel counterpart, for its fuel savings of up to 30 percent in the urban cycle.<sup>287</sup> The lithium-ion battery with a capacity of 1.9 kWh supplies the electric motor, which assists the diesel engine in accelerating and driving up a hill, with energy.<sup>288</sup>

### **MAN TGL 12.220 Hybrid, MAN eTruck and MAN CitE**

The diesel-electric hybrid truck of MAN made its debut at the IAA Commercial Vehicles in 2010. MAN's hybrid energy management system coordinates the interactions between the four-cylinder common-rail diesel engine, the 60 kW electric motor, energy storage, driving axle, and auxiliary units. This allows functions like start/stop, recuperation of braking energy, support of the diesel engine when accelerating (boosting) and electrically-powered driving.<sup>289</sup> Eight years later, MAN announced that

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<sup>284</sup> DAF (2018), URL see Bibliography

<sup>285</sup> Ibid.

<sup>286</sup> HINO TRUCKS (2016), URL see Bibliography

<sup>287</sup> IVECO, URL see Bibliography

<sup>288</sup> Ibid.

<sup>289</sup> Nadelhofer, D. (2011), URL see Bibliography

nine different transport companies will test the fully electric MAN eTruck with a GVW range of 18 to 26 tonnes and a maximum driving range of 200 kilometres.<sup>290</sup> MAN also presented a fully electric 15 tonnes concept truck called CitE for delivering goods in urban areas at the International Automobile Exhibition (IAA) in 2018.<sup>291</sup>

### **Mercedes-Benz Atego Hybrid, Mercedes-Benz eActros and Freightliner eM2 106**

The Atego has a parallel hybrid system with a lithium-ion battery pack mounted on the frame of the trailer vehicle, which allows recuperation of brake energy and electric starting in city centres or environmental zones. The electric motor assists the diesel engine during acceleration and thereby leads to fuel consumption and CO<sub>2</sub> emissions savings. Market launch of the Atego BlueTec Hybrid was in 2010.<sup>292</sup> The eActros is a fully electrified 26 t truck for delivery operations in urban areas. The lithium-ion battery packs with a capacity of 240 kWh offer a range of up to 200 km and market trials of the truck started in 2018.<sup>293</sup> In the United States, Daimler Trucks presented in 2018 the battery electric Freightliner eM2 106 designed for emission-free delivery operations in urban settings. It comes with an electric driving range of around 370 kilometres.<sup>294</sup>

### **RENAULT TRUCKS D Z.E. and Volvo FL Electric**

Renault presented in 2018 its second generation of electric trucks with a GVW range from 3.1 to 26 tonnes and tailored for city delivery and refuse collection operations. The company incorporated the findings of real-world tests with customers, which took place over the course of the last ten years, into the electric trucks' development and will offer them for sale in 2019. The lithium-ion battery of the 16 t medium-duty Renault Trucks D Z.E. allows a driving range of up to 300 kilometres, but transport companies can opt to buy a truck with a tailored range capability that suits the transport companies needs regarding costs, payload and driving range.<sup>295</sup> The 16 t Volvo FL Electric has similar specifications like the Renault Trucks D Z.E., as the truck

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<sup>290</sup> MAN Truck Germany (2018a), URL see Bibliography

<sup>291</sup> MAN Truck Germany (2018b), URL see Bibliography

<sup>292</sup> Mercedes-Benz UK (2010), URL see Bibliography

<sup>293</sup> Daimler AG (2018a), URL see Bibliography

<sup>294</sup> Daimler AG (2018b), URL see Bibliography

<sup>295</sup> Renault Trucks (2018), URL see Bibliography

manufacturer Renault Trucks belongs to its parent company Volvo Trucks. Both trucks can be fully recharged with a 150 kW rapid charger in less than 2 hours.<sup>296</sup>

### **Scania Plug-in Hybrid Electric Truck**

In 2018, Scania revealed its parallel Plug-in Hybrid Electric Truck at the International Automobile Exhibition (IAA), which combines an engine using either hydrotreated vegetable oil (HVO) or diesel fuel with an electric drivetrain offering a fully electric driving range of 10 kilometres.<sup>297</sup> The truck is praised for reducing CO<sub>2</sub> emissions up to 92 percent when the engine is fuelled with HVO.<sup>298</sup> According to officials from Scania, the truck can be used for delivery operations in noise-sensitive areas at night.<sup>299</sup>

### **Smith Newton**

Smith Electric Vehicles is producing electric trucks again, after having been rescued from bankruptcy by a Chinese battery supplier. The lithium-ion battery, for which a warranty of 60 months is given, enables a range of 120 miles at the top end and is fully charged in 8 hours. The Smith Newton can demonstrate its strengths in night-time deliveries or in residential areas, where a silent operation is required.<sup>300</sup>

## **2.4 OPPORTUNITIES AND BARRIERS FOR ELECTRIC MOBILITY IN URBAN ROAD FREIGHT TRANSPORT**

The timing of the market launch of a product innovation is of utmost importance for a truck manufacturer, which aims to reap the benefits of the hard work carried out to develop the innovative commercial vehicle. Both a premature and a delayed market launch can result in a painful loss of market share for the truck manufacturer. In the

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<sup>296</sup> VOLVO GROUP (2018), URL see Bibliography

<sup>297</sup> Scania Great Britain (2018), URL see Bibliography

<sup>298</sup> Ibid.

<sup>299</sup> Ibid.

<sup>300</sup> Pink, H. (2016a), URL see Bibliography

first case, the first mover, who bears the risks and expenses of research and development and market introduction of a new technology, might be forced to leave the field to the fast follower, who has the chance to learn from the mistakes of the first mover and to offer an enhanced product to the customers. In the second case, it might be impossible to catch up with the technology leader. Therefore the ability to estimate the take-off point of an innovation in the market correctly becomes a strategic asset of the company. This can only be done satisfactorily if the drivers behind the purchase decision of the customers are understood. Even the technically most sophisticated truck will not prevail on the market if the customers do not accept it. The purchase decision process for commercial vehicles differs considerably from that for passenger cars. In contrast to passenger cars, which can be seen as a consumer good in most instances, commercial vehicles are used for business needs and therefore are regarded as a capital good. Whereas, for instance, design or brand image can be factors that consumers consider in a buying decision of a car, these emotional factors are less important or not important at all in the purchase decision of a commercial vehicle, which is mainly driven by cost considerations. This difference, which derives from the fact that a truck is an investment item, determines the choice of a modelling methodology for the purchase decision of a commercial vehicle. However, before delving into a closer examination of potential modelling methods, it will be useful to take a glance at the determinants, which facilitate the deployment of electric trucks in the commercial vehicle sector. One of the most important factors influencing the purchase decision of a commercial vehicle is the purchase price. Although up-front costs of buying an electric truck are higher due to the battery and the likely construction of charging infrastructure at the operator's depot, these costs might be recouped because of lower energy, maintenance and service costs of an electric truck compared with a diesel truck. As trucks are highly used capital goods, the upfront cost is spread "across a higher volume of lower-cost miles, increasing the return on investment."<sup>301</sup> Another feature, which promotes the deployment of electric trucks, is the predictability of routes, as the daily recurring freight tour and the topology can be taken into account to optimize the battery size, which in turn saves battery weight and battery cost.<sup>302</sup> Furthermore, the predictability of routes may alleviate the range anxiety, which acts as a barrier to the adoption of electric trucks. Also, return-to-depot

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<sup>301</sup> Electrification Coalition (2010), p. 55

<sup>302</sup> Schulz et al. (2012), p. 87

commercial vehicles have fixed time slots for charging operations at the depot and as a consequence of that are more independent of public charging infrastructure.<sup>303</sup> Moreover, fleet operators and managers might want to use electric trucks due to considerations of image and reputation as an ecologically oriented company.<sup>304</sup> Further motivators for companies to deploy electric trucks are the exemption of taxes and charges like the Congestion Charge and the T-Charge in London. Noise emissions are another factor which transport companies may take into account, especially when delivering goods at night in noise-sensitive areas like residential areas. The London Lorry Control Scheme, for example, aims to reduce the noise pollution in urban areas at nights and weekends. Accordingly, trucks with a gross vehicle weight over 18 tonnes are not allowed to use certain roads from 9 pm to 7 am on weekdays and from 1 pm on Saturday to 7 am on Monday.<sup>305</sup> Zero emission vehicles (ZEVs) are not excluded from the Lorry Control Scheme yet. Lifting the ban on zero-emission vehicles could spur the diffusion of these vehicles in the market. Electric trucks are considerably quieter than diesel trucks and are therefore ideally suited for night-time deliveries. A beneficial side-effect of the quiet operation of electric trucks is that the driving comfort for truck drivers can be improved significantly. Despite this suitability of the commercial vehicle sector for electric mobility, there are certain challenges which need to be overcome for the market success of electric trucks. Increased energy consumption of auxiliaries like the heating system in cold temperatures and battery ageing can cause a decline in the range capability of electric vehicles and thus lead to situations in which fleet operators cannot complete their tasks.<sup>306; 307</sup> Apart from the concerns of fleet managers about the ability of electric trucks to fulfill operational needs, the biggest hurdles in the adoption are the high upfront cost for the electric truck, the charging infrastructure costs and the uncertainty regarding the resale value of the truck.<sup>308</sup> Toyota removes this barrier to adoption by guaranteeing a 3 percent higher residual value for the hybrid version of its diesel truck Hino.<sup>309</sup> To put in a nutshell, customers, which use trucks in urban freight transport, have following expectations on zero emission vehicles:

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<sup>303</sup> Schulz et al. (2012), p. 87

<sup>304</sup> Taefi et al. (2016), p. 6

<sup>305</sup> LONDON COUNCILS, URL see Bibliography

<sup>306</sup> Pelletier et al. (2014), p. 2

<sup>307</sup> Taefi et al. (2016), p. 4

<sup>308</sup> Electrification Coalition (2010), p. 76f.

<sup>309</sup> Lyden, S. (2014), URL see Bibliography

- No transport payload limitations due to battery weight
- Sufficient range for the transport tasks
- Reasonable purchase price and operating costs
- Acceptable charging times to avoid loss of earnings
- Sufficient availability of battery charging points and hydrogen (H<sub>2</sub>) refuelling stations
- Sufficient maintenance and repair services and battery guarantee
- A high lifetime of batteries
- Good driving characteristics
- Resale value comparable to that of diesel trucks
- Exemption from taxes or charges<sup>310</sup>

The following change rate is used for figures given in British pound throughout the dissertation:

$$£1 = €1.1353$$

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<sup>310</sup> Daimler AG

### 3. TRANSPORT MODE CHOICE MODEL

In classical consumer theory, the decision problem of the rationally behaving individual is solved by choosing a consumption bundle of quantities, which provides him with the highest utility. The prices of the quantities and the individual's preferences and budget thereby define the consumption decision for all alternative consumption bundles.<sup>311</sup> However, the consequence of price as single product characteristic is that the theory cannot deal with product quality variations and their effect on consumption decisions. Lancaster, therefore, suggests a new approach, in which the utility and consequently the choice of alternatives are derived from the properties or characteristics of these alternatives.<sup>312</sup> It is important to note that both the classical consumption theory and the extension of that theory by Lancaster describe a continuous decision problem, whereas the decision problem of a transport company investing in a capital good is discrete. The shortcoming of classical consumer theory to depict discrete choices is overcome with discrete choice models, which also became the standard tool in freight transport demand modelling.<sup>313</sup>

The focus of the dissertation is on the choice of a truck drivetrain technology by transport companies. In freight transport demand modelling, it is common to distinguish between aggregate and disaggregate models.<sup>314</sup> In contrast to aggregate freight demand models, which use an aggregate share of a transport mode as the basic unit of observation, disaggregate models use the decision made by a decision maker as the unit of observation.<sup>315</sup> Thereby disaggregate models allow capturing the characteristics of the decision-maker and his decision-making process.<sup>316</sup> Transport companies are guided by the principle of profit maximization or logistic costs minimization when making a transport mode choice decision.<sup>317</sup> One option to determine the demand for a transport mode, which minimizes the logistic costs, is to derive it from the cost function using Shephard's Lemma.<sup>318</sup> However, this aggregate model has the drawback that it derives the demand for the chosen transport mode but

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<sup>311</sup> Ben-Akiva, M. and Lerman, S. (1985), p. 39

<sup>312</sup> Lancaster, K. (1966), p. 133

<sup>313</sup> BVU, TNS, KIT (2016), p. 35

<sup>314</sup> Winston, C. (1983), p. 419

<sup>315</sup> Romàn, C. (2017), p. 5

<sup>316</sup> *ibid.*

<sup>317</sup> BVU, TNS, KIT (2016), p. 35

<sup>318</sup> Bühler, G. (2006), p. 71

is not suited to provide choice probabilities for alternative transport modes.<sup>319</sup> Choice probabilities of different truck drivetrain technologies can be calculated with so-called disaggregate discrete choice models, which are based on the random utility theory.<sup>320</sup> The main purpose of discrete choice models is to analyse the choice of decision-makers among different alternatives of a choice set, which needs to be exhaustive. This means that the decision-maker may choose between all possible alternatives. Other properties of the choice set are that the number of alternatives must be finite and the alternatives must be mutually exclusive.<sup>321</sup> The decision-maker in this dissertation corresponds to the customer of commercial vehicles, who has the choice between different drivetrain technologies and chooses the technology which maximizes his utility. As the primary purpose of the transport company is profit maximization, the company's utility derived from the choice of a truck type is dependent on "the difference between total revenue and total cost [...] Consequently, the concept of random utility maximization of freight mode choice is also a part of the concept of net profit maximization by the firm."<sup>322</sup> It is assumed that the revenue function of truck customers does not change throughout the analysed simulation period, as the nature of the transport service does not change. Therefore, it is sufficient to investigate the costs that are associated with the use of different drivetrain technologies. In addition to costs, the choice of a truck drivetrain technology is related to other factors like range or infrastructure availability. These factors will be described and integrated into the utility function along with cost components in chapter 3.6.

In the next chapters, the freight transport market structure, the random utility theory, and discrete choice models will be explained, followed by a deeper investigation of the theory of rational inattention and the existence of rational inattentive behaviour in freight transport. The last three chapters deal with the possibility of including the rational inattention theory in discrete choice models, the definition of utility functions and the parameter weights of the utility functions that are taken from the literature.

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<sup>319</sup> Bühler, G. (2006), p. 72

<sup>320</sup> Train, K. (2002), p. 22

<sup>321</sup> Ibid., p. 16

<sup>322</sup> Kim, H. C. (2014), p. 22

### 3.1 FREIGHT TRANSPORT MARKET STRUCTURE

In a monopolistic market, the monopolist is the single product supplier and therefore faces a downward-sloping demand curve. To increase the output quantity, the monopolist needs to decrease the product price. Therefore, the revenue of the monopolist does not only depend on the output quantity  $x$  but also indirectly on the product price  $p(x)$ .<sup>323</sup> The monopolist aims to maximize the profit  $G(x)$ , which is equivalent to maximizing the difference between revenues  $E(x)$  and costs  $K(x)$ .<sup>324</sup>

$$G_i(x) = E_i(x) - K_i(x) = p(x) \cdot x - K(x) \quad (4)$$

The maximum profit of a monopolist is achieved at the output quantity, where the marginal revenue is equal to the marginal cost.<sup>325</sup>

$$p + \frac{\partial p}{\partial x} x = \frac{\partial K}{\partial x} \quad (5)$$

The profit function of the monopolist shows that there is an interdependence between demand and price. This is known as price elasticity of demand, which measures the percent change in demand in response to a one percent change in price. One has to distinguish between own-price-elasticity and cross-price elasticity. Own-price-elasticity shows how strong the demand for a good changes as a result of a one percent change in the price of the good itself, whereas the cross-price elasticity shows how strong the demand for a good changes as a result of a one percent change in the price of an alternative good. It is thus possible to vary total truck demand depending on truck prices.

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<sup>323</sup> Woeckener, B. (2014b), p. 4f.

<sup>324</sup> Woeckener, B. (2014a), p. 2

<sup>325</sup> Ibid., p. 121

The demand for the monopolist's product also depends on the substitutability of its product by similar products. The better substitutes these products are, the more elastic is the demand for the monopolist's product.<sup>326</sup>

Generally speaking, the own-price-elasticity of demand is lower for tractor trailers and heavy-duty trucks than for medium and light duty trucks. As R&D costs can be passed to the customers more easily, innovations in the trucking business normally were applied in heavier truck classes at first.<sup>327</sup> In the case of electric mobility, this will not be the case, as it is not practical to drive tractor-trailers electrically over very long distances at the moment and these trucks are not used for urban freight transport. Therefore, electric drivetrains will start diffusing in lower truck classes.

In this dissertation, the total number of trucks demanded does not vary depending on truck prices, but truck price variations shift the demand for the truck drivetrain technologies. Furthermore, the intention of the dissertation is not to forecast the exact number of trucks in the market at the end of the simulation period, but the market-sharing between the different drivetrain technologies.

The cross-price elasticities between road freight transport and other transport modes like rail or shipping are not taken into account, as these transport modes do not come into question for urban freight transport. As there are not any serious alternatives for the last mile delivery and access regulations and requirements of the shipper often dictate the use of trucks, the price elasticity of demand for urban delivery trucks is very low.<sup>328</sup> Thus, it can be assumed that the cross-price elasticity of total truck demand is rather inelastic. Here it is assumed that there is no competition between trucks and other transport modes for urban freight transport and that price changes for transport modes like rail or shipping, therefore, do not affect the total number of demanded trucks for urban freight transport.

Although fuel consumption differences between drivetrain technologies play a significant role in the purchase behaviour of truck customers, it is assumed that the total number of trucks demanded is inelastic to fuel prices. Reasons for this may be attributed to a competitive environment, in which transport companies operate<sup>329</sup> or a

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<sup>326</sup> Woeckener, B. (2014a), p. 121

<sup>327</sup> Schmidt, V. (1993), p. 205

<sup>328</sup> Ruesch, M. (2004), p. 898

<sup>329</sup> Winebrake et al. (2015), p. 174f.

contract structure, which allows transport companies to pass along their fuel expenditures directly to the shipper.<sup>330</sup> A recent study for the UK showed that the fuel price elasticity for rigid trucks demand is -0.15.<sup>331</sup> However, this is only true for a market in which truck customers do not have the availability to switch to other drivetrain options with lower energy costs.

In contrast to a monopolist, the profit of an oligopolist depends on the actions of the other oligopolists, what leads to a situation, in which the optimal solution is a result of game theoretic considerations. This profit-maximizing solution is called Nash equilibrium, which is achieved by mutually best responses of the market players.<sup>332</sup> In a market with a homogenous good and price competition, market players are not able to make any profits, as a market player with a product price higher than the marginal cost would lose its total market share to competitors.<sup>333</sup> Product differentiation can reduce this high intensity of competition. A distinction is made between horizontal and vertical product differentiation.

When product variants with the same price differ in their characteristics, and different customers choose different product variants due to their preferences, then it is a horizontal product differentiation. Because of these customer preferences, market players do not lose their total market share when they increase their prices.<sup>334</sup>

When the product variant prices are equal, and all customers choose the product variant with the highest quality, then it is a vertical product differentiation.<sup>335</sup> In reality, product variants with high and low quality coexist in a market. However, this is only possible when the product variants with lower quality are cheaper.<sup>336</sup>

The basic model of horizontal product differentiation is called the Hotelling model<sup>337</sup> and shall be explained in greater detail in the following. For the explanation of the Hotelling model, it is assumed that customers can choose between two product variants that differ in one product characteristic. For example, such a product characteristic can be the sugar content of two soft drink variants. As the product

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<sup>330</sup> Aarnink et al. (2012), p. 24

<sup>331</sup> Wadud, Z. (2016), p. 16

<sup>332</sup> Woeckener, B. (2014a), p. 155

<sup>333</sup> Ibid., p. 175

<sup>334</sup> Woeckener, B. (2014b), p. 16f.

<sup>335</sup> Ibid., p. 16

<sup>336</sup> Woeckener, B. (2014a), p. 176

<sup>337</sup> Ibid., p. 189

variants only differ in one product characteristic, they can be placed on the one dimensional Hotelling line according to their sugar content. In this case, the soft drinks variants are positioned at both ends of the Hotelling line, as it is assumed that the product differentiation is maximal.<sup>338</sup> The customers have a preference for the sugar content of the soft drinks and are also placed on the Hotelling line according to the ideal variant they would prefer. When there is an equal distribution of the customers on the Hotelling line, and the variant prices are the same, the market share of both variants is 50%. The maximum willingness to pay by a customer for a variant decreases with increasing distance of its ideal variant and the considered variant on the Hotelling line. This difference in the observed characteristic between the ideal variant and the considered variant is called a mismatch.<sup>339</sup> The market shares of both variants on the Hotelling line are derived from the preferences of those customers that are indifferent between both product variants. Customers that are located on the left-hand side from the location of the indifferent customers select the variant on the left end of the Hotelling line, whereas the rest of the customers selects the variant on the right end of the Hotelling line.<sup>340</sup>

For the explanation of the vertical product differentiation, it is assumed that two market players M1 and M2 offer the product variants V1 and V2 that differ qualitatively regarding a product characteristic, whereby the quality of V2 is higher than the quality of V1. An example of such a vertical product differentiation is the horsepower of a truck. The willingness to pay for a variant is the multiplication of the quality level  $v$  with the maximal willingness to pay for a quality unit  $\theta$ , and the consumer surplus  $r$  is defined as:<sup>341</sup>

$$r_i = v_i * \theta - p_i \quad (6)$$

Customers are heterogeneous about the willingness to pay for a quality unit. The willingness to pay for a product variant rises with increasing product quality. In the following example, it is assumed that there is a lower and upper bound for the willingness to pay for a quality unit and customers are equally distributed between these bounds. The customer chooses the product variant that provides him with a

<sup>338</sup> Woeckener, B. (2014a), p. 189f.

<sup>339</sup> Ibid., p. 190

<sup>340</sup> Ibid., p. 191f.

<sup>341</sup> Woeckener, B. (2014b), p. 99f.

higher consumer surplus at a given willingness to pay for a quality unit. A higher product price accompanies a higher product quality. If both variants have the same price, all customers will choose the variant with the higher quality, as the high-quality variant is associated with a higher consumer surplus. However, when the product variant with the lower quality is cheaper, then both products can coexist on the market. The willingness to pay for a quality unit, at which customers are indifferent between both product variants, determines the market share of both product variants. Customers on the left-hand side of this indifference address choose the low-quality variant, whereas the customers on the right-hand side choose the high-quality variant.<sup>342</sup> This indifference address is defined as:

$$\theta_{in} = \frac{p_2 - p_1}{v_2 - v_1} \quad (7)$$

Although the UK freight market is an oligopoly, as it is dominated by a small number of truck manufacturers and is characterized by a high number of truck customers, the oligopoly is not the underlying market structure in this dissertation. It is assumed that the truck customers decide between the product alternatives of one truck manufacturer. The truck manufacturer offers medium-duty trucks for urban freight transport and reinvests the profit it generates in the development of new drivetrain technologies and the improvement of the fuel efficiency of the diesel truck. Furthermore, it can be assumed that transport companies show logistic costs minimizing behaviour when choosing a truck drivetrain technology and reinvest the profit they generate with their trucks.<sup>343</sup> The dissertation excludes leasing and other methods of financing. Following the examples of horizontal and vertical product differentiation, the demand for a product can be seen as the aggregation of individual demand decisions of truck customers and the demand for a product is equal to its market share. Since the dissertation aims to predict the aggregate behaviour of all truck customers, this requires a thorough analysis of individual demand behaviour.

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<sup>342</sup> Woeckener, B. (2014b), p. 102

<sup>343</sup> BVU, TNS, KIT (2016), p. 35

## 3.2 RANDOM UTILITY THEORY

Discrete choice models rely on the utility maximization behaviour of decision-makers but differ from classic utility theory therein that the utility is derived from the specific characteristics of the alternatives using Lancaster's approach, instead of deriving utility from the quantity demanded.<sup>344</sup> The Utility function is defined as a function which relates the attributes  $x$  of alternatives and the socioeconomic characteristics  $s$  of the decision-maker to the utility  $U$  of the decision-maker. Following the Hotelling Model, truck customers are different and have different preferences for the different product characteristics of the trucks. For example, a study about the commercial fleet demand for alternative-fuel vehicles in California has found out that:

larger fleets have a greater potential for innovation, and are more likely candidates to adopt alternative fuels. Larger numbers of vehicles allow more flexibility in re-assigning vehicles among tasks. Larger fleets are more likely to have on-site refueling and maintenance services, leading to even more flexibility in vehicles usage patterns. It is also possible that larger firms reach decisions differently from smaller firms, and are more likely to set policies that take into consideration broader social issues and/or longer term strategic concerns. Hence, they might be more willing to experiment with newer and "riskier" automotive technology.<sup>345</sup>

The truck customer  $n$ , who is confronted with different drivetrain technologies, will select the truck type which maximizes his utility. This can be stated as:

select truck type  $i$  over  $j$  if:  $U_{in} > U_{jn}$ .

As the analyst cannot observe the utility of decision-makers, he needs to treat them as random variables. The random utility theory thereby can deal with situations, in which truck customers with supposedly the same characteristics and the same choice set decide to choose different alternatives. These inconsistencies result from the analyst's inability to understand the choice situation fully, in the sense that he might not include all decision relevant attributes of the truck alternatives and the socioeconomic characteristics of the decision-makers or make mistakes in the measurements of the included attributes, might have an incomplete understanding of the preferences and the decision making process of the truck customers or might use inappropriate instrumental variables.<sup>346</sup> The random utility theory accounts for the fact that the

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<sup>344</sup> Bühler, G. (2006), p. 73

<sup>345</sup> Golob et. al (1997), p. 220 f.

<sup>346</sup> Ben-Akiva, M. and Lerman, S. (1985), p. 56

researcher has an incomplete understanding or lack of information regarding the choice of the truck customer by introducing a random error component in addition to the systematic component of the utility function, which the researcher observes. Thus, this random error component captures the “unobserved tastes, preferences and characteristics of the” transport company.<sup>347</sup>

The random component represents the difference between the utility of the truck customer and the utility, which the researcher estimates:

$$U_{in}(x,s,\epsilon)=V_{in}(x,s)+\epsilon_{in} \quad \forall i \quad (8)$$

$U_{in}$ : True Utility

$V_{in}$ : Systematic components of the utility of  $i$ , observed by the analyst

$\epsilon_{in}$ : Random components of the utility of  $i$ , unobserved by the analyst

$x$ : Vector of product characteristics  $x_{in}$  (e.g., purchase price, energy costs)

$s$ : Vector of socioeconomic characteristics  $s_n$  (e.g., economic sector, fleet size)

The “choice is not deterministic and cannot be predicted exactly”, as  $\epsilon$  is unknown to the analyst.<sup>348</sup> “The unobserved terms are considered random with density  $f(\epsilon)$ ”, which allows the analyst to derive choice probabilities.<sup>349</sup> Both parts of the utility function must be specified.

#### Specification of the systematic component of the utility function

For reasons of simplification, the observed part of utility is often assumed to be linear in parameters with a constant, although it can have any mathematical form:

$$V_{in}(x)=\beta_{i0} *ASC_i +\beta_k *x_{ink} +\phi_m *s_{mn} \quad \forall i \quad (9)$$

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<sup>347</sup> Kim, H. C. (2014), p. 22

<sup>348</sup> Train, K. (2002), p. 4

<sup>349</sup> Ibid., p. 4

For example:

$$V_{in}(x) = \beta_{i0} * ASC_i + \beta_1 * x_{in1} + \beta_2 * x_{in2} + \dots + \beta_k * x_{ink} + \varphi_1 * s_{1n} + \dots + \varphi_m * s_{mn}$$

$\beta_{i0}$ : Alternative specific constant for product i

$ASC_i$ : Indicator function (1 for alternative i, 0 otherwise)

$\beta_k$ : Parameter, which indicates the weight and effective direction of the alternative characteristic k

$x_{ink}$ : Value of characteristic k of alternative i for decision-maker n

$\varphi_m$ : Parameter, which indicates the weight and effective direction of the socioeconomic characteristic m

$s_{mn}$ : Socioeconomic characteristic m of decision-maker n

“The alternative-specific constant for an alternative captures the average impact on utility of all factors that are not included in the model [...] When alternative-specific constants are included, the unobserved portion of utility,  $\varepsilon_{nj}$ , has zero mean by construction.”<sup>350</sup> Generally, the Maximum Likelihood Estimation method is used to find the parameters of the utility function. These coefficients measure the effect of a change in the attributes of the alternative, the socioeconomic characteristics of the decision-maker and the alternative specific constant on the probability of choosing the alternative. Since only differences in utility are important, an infinite number of values for  $\beta_{i0}$  and  $\varphi$  with the same difference would generate the same choice probability.<sup>351</sup> Hence, this would make the estimation impossible. The alternative specific constants  $\beta_{i0}$  and the parameters of the socioeconomic characteristics  $\varphi$  can therefore only be estimated if they are normalized.<sup>352</sup> One of the constants and one of the socioeconomic characteristics respectively need to be set to zero to achieve this.<sup>353</sup> It is standard practice to “set the preference related parameters for one alternative, called the base or reference alternative, to zero and to re-interpret the remaining

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<sup>350</sup> Train, K. (2002), p. 25

<sup>351</sup> Ibid., p. 25f.

<sup>352</sup> Ibid., p. 26

<sup>353</sup> Ibid.

parameters to represent preference differences relative to the base alternative.”<sup>354</sup> In this dissertation, the diesel truck is chosen as reference alternative. It is conceivable that socioeconomic characteristics affect the way the decision-maker evaluates the attributes of the alternatives. Firms with a greater fleet size might place less value on driving range capabilities of battery electric trucks, as the diesel trucks in their fleet still would be employed for long range operations. By contrast, a transport company with one truck would put a high emphasis on the driving range capability of a battery electric truck. To account for the fact that the importance of range capabilities of trucks declines with the fleet size, one might consider creating a new attribute range divided by fleet size. In this case, the coefficients of the socioeconomic characteristics do not need normalization, as “the socio-demographic variables affect the differences in utility through their interaction with the attributes of the alternatives.”<sup>355</sup>

#### Specification of the random component of the utility function

“Different discrete choice models are obtained [...] from different assumptions about the distribution of the unobserved portion of utility”.<sup>356</sup> It must be born in mind that the specification of the distribution of the random errors is connected with the specification of the systematic component of the utility function, as the error term captures effects, which the researcher cannot observe.<sup>357</sup> The best known and most frequently used discrete choice models are Logit, Probit, Nested-Logit as a representative of the Generalized Extreme Value Models (GEV) and Mixed Logit.

The probability that decision-maker  $n$  chooses alternative  $i$  over all other alternatives is equal to the probability that the utility of alternative  $i$ ,  $U_{in}$ , is higher than the utility of all other alternatives:<sup>358</sup>

$$P_{ni} = \text{Prob}(U_{in} > U_{jn} \forall j \neq i) \quad ( 10 )$$

$$= \text{Prob}(V_{in} + \varepsilon_{in} > V_{jn} + \varepsilon_{jn} \forall j \neq i)$$

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<sup>354</sup> Koppelman, F. and Bhat, C. (2006), p. 36

<sup>355</sup> Train, K. (2002), p. 28

<sup>356</sup> Ibid., p. 20

<sup>357</sup> Ben-Akiva, M. and Lerman, S. (1985), p. 65f.

<sup>358</sup> Train, K. (2002), p. 20

$$\begin{aligned}
&= \text{Prob}(\varepsilon_{jn} - \varepsilon_{in} < V_{in} - V_{jn} \quad \forall j \neq i) \\
&= \int (\varepsilon_{jn} - \varepsilon_{in} < V_{in} - V_{jn} \quad \forall j \neq i) * f(\varepsilon)
\end{aligned}$$

From the last two forms of the equation ( 10 ) we can see that the choice probabilities are only affected by the differences in utilities but not their absolute levels. This means that attributes which do not capture differences between truck alternatives cannot be estimated.

### 3.3 DISCRETE CHOICE MODELS

As has already been noted, different choice models are derived depending on the specification of the density  $f(\varepsilon)$  of unobserved factors. Multinomial Logit, Conditional Logit, and Nested-Logit Models “are derived under the assumption that the unobserved portion of utility is distributed iid extreme value and a type of generalized extreme value, respectively”.<sup>359</sup> The Multinomial Logit Model is the most prominent discrete choice model. It is employed when the data contains only the socioeconomic characteristics of the decision makers. The objective of a multinomial logit model is to understand which firm characteristics determine the choice of a truck alternative. By this way, it is possible to estimate which existing truck alternative new customers with a set of firm characteristics would choose. But it is apparent that the choice of a truck alternative is not only conditioned on the firm characteristics, but also the attributes of the truck alternatives. For this case, McFadden has developed the Conditional Logit Model (also called the McFadden Logit Model), which includes both characteristics of the decision-maker and the characteristic of choice alternatives.<sup>360</sup> The Conditional Logit Model explains which product attributes and firm characteristics determine the choice of a truck alternative. This enables to estimate the choice probability of a new truck alternative with a set of product characteristics. The focus of the dissertation is to estimate the market shares of new drivetrain technologies for trucks. Furthermore, the assumption is that the utility of electric trucks depends on company characteristics like

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<sup>359</sup> Train, K. (2002), p. 20

<sup>360</sup> Greene, W.H. (2012), p. 802

the fleet size of the company. For these reasons, the Conditional Logit Model needs to be chosen for the analysis of the adoption of electric trucks by transport companies. What sets Multinomial and Conditional Logit Models apart from the Probit and Mixed-Logit Model and at the same time explains their wide dissemination in choice modelling is that they have a closed form for the choice probabilities.<sup>361</sup> This enables the use of the Maximum Likelihood Method to estimate the parameters of the utility function, which otherwise would have to be estimated with more complex simulation or numerical integration.<sup>362</sup> In the following chapter, the Conditional Logit Model is analysed in detail regarding its suitability to explain the adoption of electric trucks.

As mentioned above, the random error terms are distributed independently, identically extreme value. This distribution form is also called Gumbel and has the following density function and cumulative distribution:

$$f(\varepsilon) = \mu e^{-\mu(\varepsilon-\eta)} \exp(-e^{-\mu(\varepsilon-\eta)}) \quad (11)$$

$$F(\varepsilon) = \exp(-e^{-\mu(\varepsilon-\eta)}) \quad (12)$$

with  $\eta$  as location parameter and  $\mu$  as scale parameter. The distribution with a mean of  $\eta + \frac{0.577}{\mu}$  has a variance of  $\frac{\pi^2}{6\mu^2}$ .<sup>363</sup>

The logit probability of choosing an alternative from the choice set  $C_n$  is:<sup>364</sup>

$$P_n(i) = \frac{\exp^{V_{in}}}{\sum_j \exp^{V_{jn}}} \quad (13)$$

With the systematic part of the utility  $V_{in} = \beta_{i0} * ASC_i + \beta_k * x_{ink} + \phi_m * s_{mn}$ , the probability of choosing an alternative  $i$  can be written as:

<sup>361</sup> Train, K. (2002), p. 4f.

<sup>362</sup> Ibid., p. 5f.

<sup>363</sup> Ben-Akiva, M. and Lerman, S. (1985), p. 104f.

<sup>364</sup> Ibid., p. 103

$$P_n(i) = \frac{\exp^{\beta_{i0} * ASC_i + \beta_k * x_{ink} + \varphi_m * s_{mn}}}{\sum_j \exp^{\beta_{j0} * ASC_j + \beta_k * x_{jnk} + \varphi_m * s_{mn}}} = \frac{\exp^{\beta_{i0} * ASC_i} * \exp^{\beta_k * x_{ink}} * \exp^{\varphi_m * s_{mn}}}{\sum_j \exp^{\beta_{j0} * ASC_j} * \exp^{\beta_k * x_{jnk}} * \exp^{\varphi_m * s_{mn}}} = \frac{\exp^{\beta_{i0} * ASC_i} * \exp^{\beta_k * x_{ink}}}{\sum_j \exp^{\beta_{j0} * ASC_j} * \exp^{\beta_k * x_{jnk}}}$$

As the socioeconomic characteristics are the same for all alternatives, they drop out of the probability function. The utility function has to be modified to capture the effects of decision-maker characteristics. Greene suggests the definition of dummy variables, which are then multiplied with  $s_n$ .<sup>365</sup> If it is believed that fleet size affects the choice probability of electric trucks, one can include the regressor fleet size in the utility function by multiplying it with an alternative-specific dummy variable. By this way, fleet size is captured as an alternative specific variable and does not fall out of the probability function. The variable FleetSize-PHEV, for example, would capture the effect of fleet size on the utility of a plug-in hybrid electric truck.

The choice probabilities for the truck alternatives lie in the interval [0,1] and the probabilities of choosing the alternatives sum up to one.<sup>366</sup>

$$0 \leq P_n(i) \leq 1, \forall i \in C_n \quad (14)$$

$$\sum_{i \in C_n} P_n(i) = 1 \quad (15)$$

However, the Conditional Logit Model has one significant disadvantage, namely the Independence from Irrelevant Alternatives.

<sup>365</sup> Greene, W.H. (2012), p. 802

<sup>366</sup> Ben-Akiva, M. and Lerman, S. (1985), p. 103

### **Independence from Irrelevant Alternatives Property (IIA)**

This property states that the ratio of the choice probabilities of any two alternatives is unaffected by the attributes or presence of non-chosen third alternatives.<sup>367</sup>

$$\frac{P_n(i)}{P_n(l)} = \frac{\frac{e^{V_{in}}}{\sum_j e^{V_{jn}}}}{\frac{e^{V_{ln}}}{\sum_j e^{V_{jn}}}} = \frac{e^{V_{in}}}{e^{V_{ln}}} = e^{(V_{in}-V_{ln})} \quad ( 16 )$$

The following example shall explain the ramifications resulting from the IIA property. Consider a choice situation, in which transport companies have the choice between rail and a blue diesel truck. We assume that the choice probabilities are 50 percent for both transport modes. When a red diesel truck is added to the choice set, we expect that the choice probability of the rail option remains the same and the differently colored diesel trucks have a choice probability of 25 percent. However, when using the Conditional Logit Model, the alternatives have an equal choice probability of 1/3. This phenomenon is known as the red bus/blue bus problem.<sup>368</sup> One of the properties of a Gumbel distribution, namely that the errors terms are independent of each other, is violated, as the stochastic parts of the utility of the differently colored trucks are correlated. Whenever the unobserved parts of different alternatives in a choice are correlated, the use of a logit model is not appropriate, as it might lead to estimation errors and unrealistic market forecasts. Instead, the Nested-Logit Model can be used to overcome the problem with correlated errors. Other strategies to cope with correlated errors is to specify the deterministic part of utility in a way that the stochastic part of utility is white noise or use the Conditional Logit Model as an approximation.<sup>369</sup> Especially the inclusion of socioeconomic characteristics in an appropriate way increases the chance of getting robust forecasts.<sup>370</sup> However, there are two advantages to the IIA property of the Conditional Logit Model. The IIA property is practical, “when the researcher is only interested in examining choices among a subset of alternatives and not among all alternatives.” A second benefit of the IIA

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<sup>367</sup> Ben-Akiva, M. and Lerman, S. (1985), p. 108

<sup>368</sup> Train, K. (2002), p. 54f.

<sup>369</sup> Ibid., p. 43

<sup>370</sup> Ben-Akiva, M. and Lerman, S. (1985), p. 111

property is that it allows the inclusion of new truck alternatives without re-estimation of the model. This is possible, as an additional term in the denominator of the choice probability equation ( 13 ) does not change the odds of the previous alternatives being chosen. However, the choice alternatives must be totally different and independent from each other.<sup>371</sup>

### **3.4 ENERGY EFFICIENCY PARADOX IN FREIGHT TRANSPORT**

A point of critique refers to the fact that random utility theory assumes an omniscient decision-maker in the sense that he is able to gather and process all relevant information and make a sound decision between alternatives, which offers him the highest utility. Instead of perfect rationality, Sims coins the term rational inattention, as he believes that individuals choose options without perfect information.<sup>372</sup> Research on purchase behaviour of heavy goods vehicles customers has shown that firms do not systematically compare the upfront cost of fuel-saving technologies with associated future fuel savings and make decisions by this calculation.<sup>373</sup> As a result of this, they forfeit the chance to invest in technologies that would be beneficial to them and the society. This phenomenon, which is known as the energy efficiency paradox or energy efficiency gap, puts the use of the Total Cost of Ownership (TCO) methodology as means to analyse the diffusion of alternatively propelled trucks into the market into question. The uncertainty about the TCO benefits of electric trucks paired with slim margins in the trucking business might lead to a situation in which the cheapest truck is bought.<sup>374</sup> This applies in particular to small sized fleet companies, which anyway commonly have insufficient funds to burden the high upfront cost of efficient trucks that might generate future fuel savings.<sup>375</sup> It is estimated that heavy goods vehicle operators with a fleet of less than ten vehicles make up about 94 percent of all heavy goods vehicle operators and approximately half of all heavy goods vehicle operators are driving themselves and own just one vehicle, whereas the 300 biggest fleet

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<sup>371</sup> Domencich, T. A. and McFadden, D. L. (1975), p. 70

<sup>372</sup> Sims, A. C. (2003), p. 665

<sup>373</sup> Klemick et.al. (2015), p. 154

<sup>374</sup> Punte, S. and Bollee, F. (2016), p. 10f.

<sup>375</sup> Department for Transport (2017a), p. 29

operators own 15 percent of the heavy goods vehicle stock.<sup>376</sup> A model that presumes that all truck customers base their purchase decision on the TCO calculation falls short of reality. Some truck operators might be ready to deploy electric vehicles if price parity is achieved and a minimum electric driving range is possible.<sup>377</sup> In general, there seems to be a positive correlation between importance that is attached to TCO as purchase criteria and fleet size.<sup>378</sup> Furthermore, the TCO calculation does not “reflect the risk firms bear when adopting a new tractor feature.”<sup>379</sup> Factors like the green image of electric trucks, reliability or the inconvenience associated with the missing of a satisfactory level of service and infrastructure availability are often not included in the TCO calculation but might be important in the purchase decision of truck customers.

The energy efficiency paradox manifests itself in the so-called payback gap when the payback period of transport companies is shorter than the service life of the truck and thus not long enough to recoup the higher investment costs with lower fuel costs.<sup>380</sup> This leads to a rejection of technologies with a positive net present value.

The energy efficiency paradox in freight transport can be explained by several factors, which will be described in the following in greater detail. Customers might be uncertain about the real-world performance of truck technologies, as the fuel consumption of a truck does not only depend on the duty cycle, which determines the mileage and shares of highway and city routes, but also on the road conditions, topography, type of good and driving style.<sup>381</sup> Due to this heterogeneity in urban freight operations, knowledge spillover effects in the commercial vehicle segment might not be as large as in the personal vehicle segment.<sup>382</sup> The uncertainty about fuel saving benefits might necessitate in-house testing of truck technologies before switching to a new technology with the whole fleet. These transaction costs might slow down the adoption of fuel-saving technologies.<sup>383</sup> Furthermore, the lack of experience with new drivetrain technologies may result in the belief that these technologies are less reliable. The belief that the risk of a costly breakdown is higher than for diesel trucks may impede the diffusion process of new drivetrain technologies. Transport companies rather

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<sup>376</sup> Department for Transport (2017a), p. 15

<sup>377</sup> Baster et al. (2014), p. 26

<sup>378</sup> Gnamm, J. and Lundgren, J. (2016), p. 2

<sup>379</sup> Klemick et.al. (2015), p. 159

<sup>380</sup> Ibid., p. 156f.

<sup>381</sup> Ibid., p. 160

<sup>382</sup> Ibid.,

<sup>383</sup> Ibid.

would wait until the bugs of the new technologies are eliminated.<sup>384</sup> Another factor that contributes to the slow adoption of fuel-saving technologies is the uncertainty about the fuel price development and consequently the doubt whether future fuel savings will be high enough to make the investment profitable.<sup>385</sup> The lack of infrastructure for refuelling and charging vehicles and a network of service stations to maintain and repair vehicles is a barrier to the adoption of electric trucks. However, without a sufficient number of electric trucks on the road, there will not be any company to invest in charging infrastructure or service stations. This phenomenon is known as chicken-egg-problem and can significantly delay the diffusion process of electric trucks.<sup>386</sup> Other explanations for the energy efficiency paradox in freight transport are financial constraints, fuel price trends and volatility and split incentives.<sup>387</sup> An example of split incentives is a contract structure that allows transport companies to pass their fuel costs to the shipper.<sup>388</sup>

A lack of information is found to be a barrier to the adoption of fuel-saving technologies.<sup>389</sup> An important explanation for the slow adoption of fuel-saving technologies by transport companies are the high costs associated with searching and evaluating the relevant information about fuel-saving measures.<sup>390</sup> Transport companies might not be aware of the existence of fuel-saving technologies or might be unsure about their fuel saving benefits.<sup>391</sup> The costly process of searching and synthesizing information about fuel-saving technologies is part of the overall transaction costs of a new drivetrain technology.<sup>392</sup> Especially for smaller transport companies, these transaction costs might pose a challenge, as these smaller transport companies generally might have less time and money to evaluate new technologies.<sup>393; 394</sup> In case of such high search costs, it would be rational to invest in fuel-saving technologies without complete information.<sup>395</sup> This behaviour is termed rational inattention and economists increasingly use the theory of rational inattention to

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<sup>384</sup> Klemick et.al. (2015), p. 162f.

<sup>385</sup> Aarnink et al. (2012), p. 28

<sup>386</sup> Klemick et.al. (2015), p. 161

<sup>387</sup> Aarnink et al. (2012), p. 24-29

<sup>388</sup> Ibid.

<sup>389</sup> Ibid., p. 24f.

<sup>390</sup> Ibid., p. 23

<sup>391</sup> Ibid., p. 26f.

<sup>392</sup> Ibid., p. 26

<sup>393</sup> Ibid., p. 27

<sup>394</sup> Dünnebeil et al. (2015), p. 50

<sup>395</sup> Klemick et.al. (2015), p. 159

explain choice decisions of market agents. Models that integrate information-processing constraints of decision makers seem to be more accurate in describing economic occurrences.<sup>396</sup> The rational inattention theory is based on the notion that people have a limited attention capacity and need to decide how they allocate the scarce resource attention when making decisions.<sup>397</sup> When transport companies with limited time and money resources have to choose between different drivetrain options, they cannot gather all relevant information about the drivetrain options but have to decide which information they concentrate on, as information acquisition is costly. The rational inattention theory states that the allocation of attention is done optimally by decision makers in the sense that they optimally weigh the benefits of information acquisition against the costs.<sup>398</sup> A characteristic of rational inattention theory is that the decision makers “choose an arbitrary information structure subject to a cost of choosing more informative structures”<sup>399</sup> and thus the way how information is processed is irrelevant for the optimal decision.<sup>400</sup> This means that the type of information source can be anything like a marketing campaign of a truck manufacturer, a personal interview with a dealer, in-house testing of trucks, an article in a trucking journal or advice from a truck driver.

### **3.5 INCLUDING RATIONAL INATTENTION INTO DISCRETE CHOICE MODELS**

The rationally inattentive decision maker is uncertain about the true values of the choice options and wants to reduce this uncertainty to choose the option which provides him with the highest utility. In rational inattention theory, entropy is the measure of uncertainty, which is reduced by information flows.<sup>401</sup> The information transmission process is illustrated using a channel with a limited capacity through which information flows. If it is assumed that the realization of the random variable  $X$  is the input data into the channel and the output data at the end of the channel is a

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<sup>396</sup> Sims, A. C. (2003), p. 666

<sup>397</sup> Wiederholt, M. (2010), p. 1

<sup>398</sup> Ibid., p. 2

<sup>399</sup> Caplin et al. (2016), p. 6

<sup>400</sup> Sims, A. C. (2003), p. 666

<sup>401</sup> Ibid., p. 667

random variable  $Z$ , whose probability distribution function is conditional on  $X$ , then the reduction in entropy is equal to the information that is acquired about  $X$  from observing  $Z$ .<sup>402</sup> The random variable  $X$  is the vector of the choice options' values  $v$  and acquiring and processing information reduces the uncertainty about the values.<sup>403</sup> Here, the truck drivetrain options  $i$  have different value levels  $v_i$  (payoff) and truck customers want to choose the drivetrain option with the highest value.<sup>404</sup> Truck customers have incomplete information about the true values of drivetrain technologies, but they can search for new information about the drivetrain technologies to reduce the uncertainty. However, truck customers have limited financial and time resources, and it might be "too costly to investigate the options to the point where their values are known with certainty."<sup>405</sup> As a result, truck customers, which are uncertain about the true values of the drivetrain options, might choose a truck that does not provide the highest utility.<sup>406</sup> The truck customers facing choice options have some prior knowledge about the values  $v$ , given by a joint distribution  $G(v)$ .<sup>407</sup> The choice of truck customers depends on this prior knowledge or beliefs about the values of the new drivetrain options.<sup>408</sup> Truck customers can increase their prior beliefs by acquiring information. They only acquire information that they find useful and process information optimally at the given cost of information.<sup>409</sup> With his posterior belief about the drivetrain technologies, the truck customers then choose the option with the highest expected value.<sup>410</sup> They thereby weigh the expected value of the selected option against the cost of information, which can be described as follows:<sup>411</sup>

$$\max_{\{P_i(v)\}} \left( \sum_{i=1}^N \int v_i P_i(v) G(dv) - \text{cost of information processing} \right) \quad ( 17 )$$

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<sup>402</sup> Sims, A. C. (2003), p. 667

<sup>403</sup> Matějka, F. and McKay, A. (2015), p. 277

<sup>404</sup> Ibid.

<sup>405</sup> Ibid., p. 272

<sup>406</sup> Ibid.

<sup>407</sup> Ibid., p. 278

<sup>408</sup> Ibid., p. 272

<sup>409</sup> Ibid., p. 273

<sup>410</sup> Ibid., p. 277

<sup>411</sup> Matějka, F. and McKay, A. (2013), p. 9

**subject to:**

$$P_i(v) \geq 0 \quad ( 18 )$$

$$\sum_{i=1}^N P_i(v) = 1 \quad ( 19 )$$

$P_i(v)$ : Probability of choosing option  $i$  when the values are  $v$

$G(dv)$ : Decision maker's prior belief

The cost of information processing is defined as  $\lambda\kappa$ , with  $\lambda$  as the cost of information per unit and  $\kappa$  as the quantity of information that is processed.<sup>412</sup> The decision maker's strategy of information processing determines how much information is processed and  $\lambda$  is a quantified parameter.<sup>413</sup> The term  $\lambda\kappa$  can be interpreted in the sense that the "cost is proportional to the expected number of questions asked."<sup>414</sup> Thus, the equation ( 17 ) above can be written as:

$$\max_{\{P_i(v)\}} \left( \sum_{i=1}^N \int v_i P_i(v) G(dv) - \lambda\kappa(P, G) \right) \quad ( 20 )$$

"The expected reduction in the entropy  $v$  is the difference between the prior entropy of  $v$  and the expectation of the posterior entropy of  $v$  conditional on the chosen option  $i$ .

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<sup>412</sup> Matějka, F. and McKay, A. (2013), p. 9

<sup>413</sup> Ibid.

<sup>414</sup> Ibid., p. 10

This quantity is also called the mutual information between  $v$  and  $i$ .<sup>415</sup> A random variable's ( $X$ ) entropy is defined as:<sup>416</sup>

$$H(X) = - \sum P(x) \log(P(x)) \quad (21)$$

With this definition, the equation for the cost of information processing takes the following form:<sup>417</sup>

$$\begin{aligned} \kappa(P, G) &= H(v) - E_i[H(v | i)] = H(i) - E_i[H(i | v)] \\ &= - \sum_{i=1}^N P_i^0 \log P_i^0 + \int \left( \sum_{i=1}^N P_i(v) \log P_i(v) \right) G(dv) \end{aligned} \quad (22)$$

“where

$$P = \{P_i(v)\}_{i=1}^N \quad (23)$$

is the collection of conditional probabilities, and  $P_i^0$  is the unconditional probability of choosing option  $i$  defined as

$$P_i^0 = \int P_i(v) G(dv) \quad (24)$$

If  $\lambda > 0$ , the probability of choosing option  $i$  is:<sup>419</sup>

$$P_i(v) = \frac{P_i^0 e^{v_i/\lambda}}{\sum_{j=1}^N P_j^0 e^{v_j/\lambda}} \quad (25)$$

<sup>415</sup> Matějka, F. and McKay, A. (2013), p. 11

<sup>416</sup> Ibid.

<sup>417</sup> Ibid.

<sup>418</sup> Ibid.

<sup>419</sup> Ibid., p. 13

The unconditional probabilities of choosing drivetrain option  $i$ ,  $P_i^0$ , only depend on the prior knowledge  $G(v)$  and the unit cost of information  $\lambda$  and not on “a specific realization of the values  $v$ .”<sup>420</sup> If truck customers do not distinguish between drivetrain options a priori and only find differences between drivetrain options once they start with information processing, the rational inattention model becomes the standard Multinomial Logit Model.<sup>421</sup> The drivetrain options are exchangeable in the customers’ prior and  $P_i^0$  is  $1/N$  for all drivetrain options  $i$ .<sup>422</sup> If  $P_i^0$  is replaced with the term  $e^{\alpha_i/\lambda}$ , the choice probabilities can be formulated as:<sup>423</sup>

$$P_i(v) = \frac{e^{(v_i + \alpha_i)/\lambda}}{\sum_{j=1}^N e^{(v_j + \alpha_j)/\lambda}} \quad (26)$$

The equation ( 13 ) for the Multinomial Logit Model has been extended to include the truck customers’ prior knowledge and information processing strategy  $\alpha$  in addition to the true values  $v$  of the drivetrain options. The parameter  $\lambda$  in the equation ( 26 ) scales the cost of information.<sup>424</sup>

With  $\alpha = \lambda \log P_i^0$ , the exponents can be rewritten as  $(v_i/\lambda + \log P_i^0)$ .<sup>425</sup> From this term, it can be seen that the higher the cost of the information is, the less the decision maker’s choice is based on the values of the choice options and more on his prior beliefs.<sup>426</sup> The term  $\alpha$  shifts the values of options  $i$  and thus the choice probabilities “towards those options that appeared to be good candidates a priori”<sup>427</sup> and thus can be seen as the a priori attractiveness of options. “As the distribution of payoffs is unspecified, we may take  $\lambda = 1$  at no loss of generality”.<sup>428</sup> In this case, the values are changed by  $\log P_i^0$ .<sup>429</sup> With  $\log 0 = -\infty$  and  $e^{-\infty} = 0$ , the drivetrain options with an unconditional probability of zero are not considered for choice.<sup>430</sup> It has to be mentioned that the

<sup>420</sup> Matějka, F. and McKay, A. (2013), p. 13

<sup>421</sup> Ibid., p. 16

<sup>422</sup> Ibid.

<sup>423</sup> Ibid., p. 3

<sup>424</sup> Ibid.

<sup>425</sup> Ibid., p. 13f.

<sup>426</sup> Ibid.

<sup>427</sup> Ibid., p. 3

<sup>428</sup> Fosgerau, M. and Melo, E. (2017), p. 6

<sup>429</sup> Ibid., p. 7

<sup>430</sup> Ibid.

truck customer is aware of all options from the beginning, but does not know the true values of the options.<sup>431</sup>

To avoid the misinterpretation of the exponent in ( 26 ) as “utility only”<sup>432</sup>, it is necessary to separate the preferences of customers  $V_i$  from their prior beliefs. As explained,  $\alpha$  can be interpreted as “the log of ex ante probability of choosing  $i$ ”<sup>433</sup> or prior beliefs. “If agents get their prior beliefs about payoffs (e.g., quality) of alternatives by observing what other people bought before them, then the market shares of goods and the ex ante probabilities of choosing the goods must coincide;  $\alpha_i$  is thus observable.”<sup>434</sup> This is one way to distinguish between preferences of customers  $V_i$  and their prior beliefs. To calculate the choice probabilities of drivetrain options, it is thus inevitable to define the unconditional choice probabilities  $\{P_i^0\}_{i=1}^N$ . But how can the unconditional choice probabilities be defined?

As described in the introduction to the dissertation, the existing socio-technical regime, which is dominated by diesel trucks, is increasingly threatened by political measures like the introduction of CO<sub>2</sub> emissions limits or a ban of highly polluting diesel trucks from inner cities and the rapid development of electric trucks regarding technological maturity and cost-effectiveness. But the adoption of electric trucks might still be hampered by certain barriers, even if they would perform better than diesel trucks. A survey of transport companies revealed that the uptake of fuel-saving technologies is slowed down by a lack of awareness about the existence of new technologies, a limited information about fuel savings, high search and information costs and a risk aversion to innovations in the transport sector as a result of the uncertainties regarding the real-world fuel benefits and the effects on the existing operations.<sup>435</sup> The heterogeneity of operations in the commercial vehicles sector makes it difficult for truck manufacturers to estimate the fuel benefits for specific customer segments. For this reason, they offer demonstration trucks in the hope to convince customers about the fuel-saving potential of their trucks.<sup>436</sup> These demonstration trucks might be necessary, as a survey found out that truck customers do not trust the quantitative fuel economy estimates of truck manufacturers, although manufacturers and dealers are

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<sup>431</sup> Matějka, F. and McKay, A. (2013), p. 7

<sup>432</sup> Mackowiak et al. (2018), p. 33

<sup>433</sup> Ibid.

<sup>434</sup> Ibid.

<sup>435</sup> Aarnink et al. (2012), p. 24

<sup>436</sup> Ibid., p. 53

one of the most important information sources. Further information sources are conferences, trade associations, and informal peer networks.<sup>437</sup> Another way to inform yourself about new truck technologies are truck related journals, which compare different trucks against each other and inform their readers about the cost champion.<sup>438</sup> Apart from fuel savings, the reliability of a truck is an important criterion in the purchase decision of a truck. As commercial vehicles are used several hours a day, a technical breakdown would cause costly downtime, what may impede the adoption of electric trucks.<sup>439</sup> Truck customers and drivers, who already have made good experiences with the deployment of electric trucks, can lower the barriers to adoption by spreading information about their fuel saving potential and their reliability.<sup>440</sup> This shows the outstanding importance of the promotion of electric trucks through the marketing efforts of manufacturers and the word-of-mouth communication between truck users when it comes to the successful diffusion of an innovation in the freight market. The preceding considerations are integrated into the discrete choice model by applying the willingness to consider concept of Struben and Sterman.<sup>441</sup> They assert that being aware of a drivetrain technology is not sufficient for customers to take it into their purchase consideration set, but they need to be familiar with and knowledgeable about the technology.<sup>442</sup> “Willingness to consider a platform captures the cognitive, emotional, and social processes through which drivers gain enough information about, understanding of, and emotional attachment to a platform for it to enter their consideration set.”<sup>443</sup> The willingness to consider (WtC) electric trucks can have values between 0 and 1 and increases with social exposure. In contrast to Struben and Stermen, it is assumed that the willingness to consider electric trucks does not decrease with a fractional decay factor. The unconditional probabilities  $\{P_i^{01}\}_{i=1}^N$  of the drivetrain options depend on their prior knowledge of truck customers about the new drivetrain options. This knowledge increases through the information channels described above. In the following, it is explained how the willingness to consider (WtC) concept is linked with the unconditional probabilities of drivetrain options.

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<sup>437</sup> Klemick et.al. (2015), p. 159

<sup>438</sup> Aarnink et al. (2012), p. 53

<sup>439</sup> Ibid., p. 24

<sup>440</sup> Klemick et.al. (2015), p. 159

<sup>441</sup> Struben, J. and Sterman, J. D. (2008), p. 1071

<sup>442</sup> Ibid., p. 1075

<sup>443</sup> Ibid., p. 1077

An increase in willingness to consider electric vehicles is caused by marketing efforts of manufacturers, positive word-of-mouth of drivers/owners of electric trucks and positive word-of-mouth of drivers/owners of diesel trucks.<sup>444</sup> This is in line with the innovation diffusion theory of Rogers.

$$\frac{d}{dt}WtC_{EV}(t)=\eta_{EV}(t)*(1-WtC_{EV}(t)) \quad ( 27 )$$

$WtC_{EV}$ : Willingness to consider electric vehicles [-]

$\eta_{EV}$ : Impact of total social exposure on the increase in familiarity with EVs [-]

Total exposure to electric trucks is defined as:<sup>445</sup>

$$\eta_{EV}(t)=\omega_{EV}+ \vartheta_{EV} * \frac{F_{EV}}{F_{Total}} +\vartheta_{ICEV} *WtC_{EV}^*(t) \left(1-\frac{F_{EV}}{F_{Total}}\right) \quad ( 28 )$$

$\omega_{EV}$ : Effectiveness of marketing and promotion for EVs [-]

$\vartheta_{EV}$ : Effectiveness of word-of-mouth contacts with drivers/owners of EVs [-]

$\vartheta_{ICEV}$ : Word-of-mouth about EVs among drivers/owners of diesel trucks [-]

$F_{EV}$ : Total Stock of Electric Vehicles [Trucks]

The innovators amongst the trucking companies are convinced by the marketing efforts of manufacturers or inform themselves with journals, by attending truck fairs or use test vehicles. These innovators then spread information about the competitiveness and suitability of electric trucks for their business amongst other transport companies. The effect of word-of-mouth from users of EVs on the increase of familiarity with EVs is higher (0.25) than the effect from non-users of EVs (0.15), as users actually made real-world experiences with electric drivetrain technologies and thus their words are

<sup>444</sup> Struben, J. and Sterman, J. D. (2008), p. 1077

<sup>445</sup> Ibid.

more trustworthy (see Table 7). The chosen values for the innovation parameter and the imitation parameters (word-of-mouth effect) are in line with the findings of Sultan et al. They analysed 213 different diffusion processes and found out that the word-of-mouth effect between customers is more important for the widespread diffusion of a product than the innovativeness of customers. The average value for the innovation and imitation parameters were 0.03 and 0.38 respectively.<sup>446</sup>

The link between the willingness to consider factor and the unconditional choice probability is established as follows. When the willingness to consider factor for electric truck options is zero, the weight  $\alpha = \log 0$  shifts the values of the electric drivetrain options by  $-\infty$ . In this way, these electric drivetrain options are eliminated from the consideration set. However, when the willingness to consider factor for electric drivetrain option is 1, the weight  $\alpha = \log 1$  gets zero, and the truck customers evaluate the drivetrain options according to their true values. Thus the choice probabilities of electric vehicles are affected by the shift weights  $\alpha = \log Wt_{C_{EV}}$ .

It is assumed that truck customers are fully informed about diesel trucks as it is the dominant drivetrain in their fleets. Therefore, they do not need to acquire information about diesel trucks and evaluate this truck type with perfect information. It has to be mentioned that it is not distinguished between different electric drivetrain options regarding the willingness to consider factor. It is assumed that truck customers acquire information about electric drivetrains in general. For example, if they attend a fair or read transport magazines, they do not only inform themselves about battery electric trucks but also plug-in hybrid electric trucks and fuel cell electric trucks. Afterwards, these first truck customers, called innovators, spread this information about electric drivetrain options. To put in a nutshell, the unconditional probabilities in this dissertation are not only defined by past market shares of drivetrain technologies like in the paper of Caplin et al.<sup>447</sup>, but also by marketing efforts of truck manufacturers and word-of-mouth contacts between transport companies or truck drivers.

Effectiveness of marketing and promotion for EVs [-]	$\omega_{EV}$	0.01
Effectiveness of word-of-mouth contacts with drivers or owners of EVs [-]	$\vartheta_{EV}$	0.25

<sup>446</sup> Sultan et al. (1990), p. 75

<sup>447</sup> Caplin et al. (2016), p. 9

Word-of-mouth about EVs among drivers or owners of diesel trucks [-]	$\vartheta_{ICEV}$	0.15
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Table 7 Values of the Willingness to Consider function<sup>448</sup>

A characteristic that sets the model of Matějka and McKay apart from the Multinomial Logit without information frictions is that “duplicate options are treated as a single option.”<sup>449</sup> Thus, the caveat of the Multinomial Logit Model that a duplicate increases the choice probability of this duplicate is not existent.

### 3.6 UTILITY FUNCTIONS

The transport companies evaluate truck alternatives regarding the criteria purchase price, fuel costs, maintenance and repair costs, driving range, CO<sub>2</sub> emissions (image), fuelling/recharging time and infrastructure and service station availability. In the following, the equations for the criteria are given:

#### Purchase Price

The purchase price is included in thousands of €.

$$\Delta V_i = \beta_1 * Price_i \quad ( 29 )$$

#### Energy Costs

The fuel costs are included in € per 100 km.

$$\Delta V_i = \beta_2 * c_{en,i} \quad ( 30 )$$

The energy costs per km for the diesel truck are calculated as the multiplication of fuel consumption in litres per km with the fuel price in € per litre. The energy costs per km

<sup>448</sup> Struben, J. and Sterman, J. D. (2008), p. 1079

<sup>449</sup> Matějka, F. and McKay, A. (2015), p. 23f.

for the battery electric truck are calculated as the multiplication of electricity consumption in kWh per km with the electricity price in € per kWh. The following graph compares the development of diesel prices and electricity prices in the UK from 2004 onwards. As can be seen from the graph, the diesel prices followed a rising trend since 2009 and declined after 2012, but are still over the £1 mark (see Figure 10). In contrast to that, the electricity price stayed nearly constant and is on a much lower level than the diesel price. Regarding electricity prices, it has to be distinguished between domestic and industrial electricity prices, which can differ considerably.

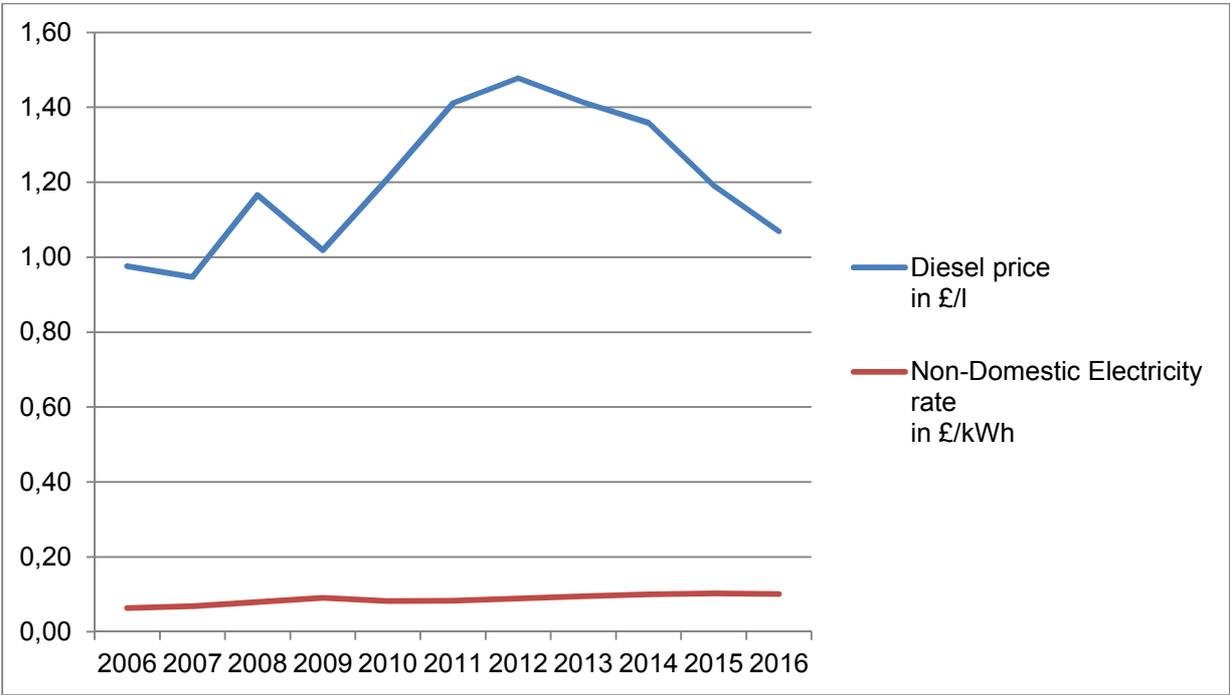


Figure 10 Diesel price<sup>450</sup> and electricity price<sup>451</sup> development in the UK from 2004 to 2016

The electricity tariffs paid by small commercial consumers are closer to those of domestic consumers, whereas the industrial electricity prices are a good reference value for larger commercial consumers.<sup>452</sup> The average retail electricity price was £0.10 for medium-sized non-domestic consumers.<sup>453</sup> The average domestic electricity price in the UK in 2016 was £0.183.<sup>454</sup> It is important to stress that managers of large

<sup>450</sup> Wilkins et al. (2016), p. 84  
<sup>451</sup> Department for Business, Energy & Industrial Strategy (2017a), Annual tab, URL see Bibliography  
<sup>452</sup> Vincent et al. (2017), p. 4  
<sup>453</sup> Department for Business, Energy & Industrial Strategy (2017a), for paper publication tab, URL see Bibliography  
<sup>454</sup> eurostat (2017), URL see Bibliography

fleets can negotiate a retail electricity price below the average retail price and ensure that the vehicles are charged at night, when the electricity rates are lower, which would further widen the fuel cost gap between diesel and electric trucks. To account for this negotiation effect and the fact that there are differently sized transport companies, the average of the two electricity price types is taken for the TCO calculation. This corresponds to an electricity price of approximately €0.161 per kWh. The fact that the development of the electricity price is not subject to volatility to the same extent as the development of the diesel fuel price provides the truck operator with the opportunity to plan the future expenditure on charging the vehicles with higher certainty. The average retail price of diesel in 2016 was £1.1013 at a crude oil price of £62.99 (\$82.11) per barrel.<sup>455</sup> This corresponds to €1.25 per litre. The energy costs per km of the battery electric truck are many times lower than the energy costs per km of the diesel truck. The energy fuel saving potential is one of the main attributes of electric drivetrains that argue for preferring an electric truck. Although the per-km energy cost of diesel trucks will decrease as a result of efficiency improvements in diesel engines, it is highly likely that rising diesel fuel prices will erode this due to an oil shortage. It has to be noted that the energy consumption is given for an average load profile. A fully loaded truck will have higher average energy consumption. The energy costs per 100 km are calculated as follows for the different truck types:

$$c_{en,ICEV} = Q_{ICEV}^{Diesel} * 100 \text{ km} * \text{Diesel Price} \quad ( 31 )$$

$$c_{en,BEV} = Q_{BEV}^{el} * 100 \text{ km} * \text{Electricity Price} \quad ( 32 )$$

$$c_{en,FCEV} = Q_{FCEV}^{el} * 100 \text{ km} * \text{Electricity Price} \quad ( 33 )$$

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<sup>455</sup> Department for Business, Energy & Industrial Strategy (2017b), Annual tab, URL see Bibliography

$$c_{en,PHEV} = \left[ \frac{D_{e,PHEV} * Q_{BEV}^{el} * \text{Electricity Price} + (133 \text{ km} - D_{e,PHEV}) * Q_{ICEV}^{Diesel} * \text{Diesel Price}}{133 \text{ km}} \right] * 100 \text{ km} \quad ( 34 )$$

$c_{en,i}$ : Energy costs of truck type i [€]

$Q_i^{el}$ : Energy consumption of truck type i [kWh/km]

$Q_i^{Diesel}$ : Fuel consumption of truck type i [l/km]

$D_{e,PHEV}$ : Electric driving range of a Plug-in hybrid electric truck [km]

The energy costs per km of a plug-in hybrid electric truck are dependent on the duty cycle. For the calculation of the energy costs per km, a daily driving range of 133 km is assumed. Accordingly, the plug-in hybrid electric truck fully depletes the battery before switching to the diesel engine. Furthermore, it is assumed that the energy consumption in the charge depleting mode is equal to the energy consumption of a battery electric truck and the fuel consumption in the charge sustaining mode is assumed to be equivalent to the fuel consumption of a diesel truck.

### **Maintenance and Repair Costs**

The maintenance and repair costs are included in € per 100 km.

$$\Delta V_i = \beta_3 * c_{mr,i} \quad ( 35 )$$

Maintenance and repair cost savings have the potential to attract especially the attention of those truck customers, which calculate with a longer holding period and a higher annual mileage for their trucks. In these cases, the maintenance and repair cost savings could offset a bigger portion of the additional capital outlay for battery electric trucks. Diesel trucks are more difficult and costlier to maintain and to repair, as they have more moving parts and wear items than battery electric trucks. Although the

costs to repair components like transmissions and the engine will rise with the increasing age of the vehicle, this has not been considered due to lack of data.

The maintenance and repair costs have been integrated into an equation following the cost assumption of the study “Zero emission trucks” from CE Delft:<sup>456</sup>

$$c_{mr,ICEV}(t) = 0.06 \frac{\text{€}}{\text{km}} * 100 \text{ km}, \quad \forall t \in \{0, 1, \dots, T-1\} \quad (36)$$

$$c_{mr,BEV}(t) = 0.04 \frac{\text{€}}{\text{km}} * 100 \text{ km}, \quad \forall t \in \{0, 1, \dots, T-1\} \quad (37)$$

$$c_{mr,PHEV}(t) = 0.05 \frac{\text{€}}{\text{km}} * 100 \text{ km}, \quad \forall t \in \{0, 1, \dots, T-1\} \quad (38)$$

$$c_{mr,FCEV}(t) = 0.04 \frac{\text{€}}{\text{km}} * 100 \text{ km}, \quad \forall t \in \{0, 1, \dots, T-1\} \quad (39)$$

$c_{mr,i}(t)$ : Maintenance and repair costs of truck type  $i$  [€]

The maintenance and repair costs of a plug-in hybrid electric truck are higher than the maintenance and repair costs of a battery electric truck, as the plug-in hybrid electric truck has two drivetrain technologies, but are lower compared with a diesel truck, as the diesel engine is used less.<sup>457</sup>

The assumption that all fleet managers or truck owners include these costs into their calculation during the purchase decision process might be misleading due to several reasons. Truck owners might pursue the strategy to sell the vehicles before important maintenance and repair dates, from which on the maintenance and repair costs begin to increase.<sup>458</sup> Another factor that may act as a deterrent are costs that are associated with special tools for handling high voltage components and the training or hiring of

<sup>456</sup> den Boer et al. (2013), p. 81

<sup>457</sup> Electrification Coalition (2010), p. 104

<sup>458</sup> Ibid., p. 93

staff to be able to maintain and repair electric trucks.<sup>459</sup> These switching costs that occur from switching to another drivetrain technology can be a barrier to adoption. In such a case fleet managers might not be convinced of the benefits of lower maintenance and repair costs of electric trucks. For these reasons, the importance of maintenance and repair costs in the purchase decision process of truck customers has to be assessed.

### **Driving Range**

The driving range is included in km. Driving range is often entered as a natural logarithm transformation in studies for the passenger car market to account for the declining marginal utility.<sup>460</sup> Following this approach, the utility of range is defined as:

$$\Delta V_i = \beta_4 * \ln(R_i) \quad (40)$$

The driving ranges of the truck types diesel truck and plug-in hybrid electric truck are assumed to be 1,000 km. The electric driving ranges of a plug-in hybrid electric truck and a battery electric truck are a function of battery capacity and energy consumption per km. The hydrogen tank is scaled to offer a range of 133 km, as by this cost and weight are saved. However, future efficiency gains of fuel cell systems will increase the maximum range despite the fixed amount of carried hydrogen. Although the low daily mileages in urban transport operations and the battery and hydrogen tank right-sizing should limit the range anxiety, customers are used to the range flexibility of a diesel truck.<sup>461</sup>

### **CO<sub>2</sub> Emissions**

Transport companies in urban freight transport are the main target group for electric truck manufacturers, as trucks used by these transport companies have high

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<sup>459</sup> Electrification Coalition (2010), p. 93

<sup>460</sup> Calfee, J.E. (1985), p. 288.

<sup>461</sup> Kay, D. and Hill, N. (2012), p. 30

visibility.<sup>462</sup> Truck customers can use these green trucks to show their environmental responsibility and to build up a green image.<sup>463</sup> The diesel truck produces tailpipe emissions, why transport companies cannot use diesel trucks to promote a green image. This leads to a disutility compared with emission-free vehicles. The CO<sub>2</sub> emissions value that is entered into the utility function is the fraction of the CO<sub>2</sub> emissions of the current vehicle technology, when the CO<sub>2</sub> emissions output of a diesel truck of 548 g per km in the first year is taken as a reference case. CO<sub>2</sub> emissions are entered as a natural logarithm transformation to account for the declining marginal disutility and are given in percent.

$$\Delta V_i = \beta_5 * \ln \left[ \left( \frac{CO_{2,i}^{TTW}}{548 \frac{gCO_2}{km}} \right) * 100 \right] \quad (41)$$

The battery electric truck and the fuel cell electric truck do not produce any tailpipe emissions. The CO<sub>2</sub> emissions of the plug-in hybrid electric truck and the diesel truck are a function of fuel consumption and CO<sub>2</sub> intensity of diesel fuel.

### **Refuelling Time**

The refuelling time is included in minutes. The refuelling time of a fuel cell electric truck is assumed to be higher than the diesel truck refuelling time, as the high pressure in hydrogen tanks increases the temperature and delays the filling process.<sup>464</sup> The refuelling time of fuel cell buses is 7-10 minutes.<sup>465</sup> It is assumed that the refuelling process of a fuel cell electric truck takes twice as long as the refuelling process of a plug-in hybrid electric truck and a diesel truck.

$$\Delta V_i = \beta_6 * T_{r,i} \quad (42)$$

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<sup>462</sup> Taefi et al. (2016), p. 8

<sup>463</sup> Baster et al. (2014), p. 25

<sup>464</sup> Teter et al. (2017), p. 100

<sup>465</sup> Den Boer et al. (2013), p. 51

$$T_{r,ICEV}=5 \text{ minutes}$$

$$T_{r,PHEV}=5 \text{ minutes}$$

$$T_{r,FCEV}=10 \text{ minutes}$$

### **Recharging Time**

The recharging time is entered as a natural logarithm transformation to account for the declining marginal disutility and is given in minutes. The charging duration of electric vehicles requires planning of daily maintenance and operational activities like washing, loading, and unloading around this charging time.<sup>466</sup> This reduces the flexibility compared with diesel trucks. Furthermore, some operators might be dependent on public charging infrastructure due to financial restrictions.

$$\Delta V_i = \beta_7 * \ln(T_{c,i}) \quad ( 43 )$$

$$T_{c,PHEV}=60 \text{ minutes}$$

$$T_{c,BEV}=240 \text{ minutes}$$

### **Infrastructure Availability**

Infrastructure availability is entered as a natural logarithm transformation of stations with appropriate fuel to account for the declining marginal utility and is given in percent. The availability of diesel fuel (100%) is taken as a reference value. There were 8,407 petrol stations in the UK in 2017. Around the turn of the millennium, the number of petrol stations was 13,107.<sup>467</sup> This can be seen as proof that the importance of carbon fuel is constantly shrinking.

$$\Delta V_i = \beta_8 * \ln(IA_i * 100) \quad ( 44 )$$

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<sup>466</sup> Quak et al. (2016), p. 1510

<sup>467</sup> statista (2017), URL see Bibliography

### **Service Station Availability**

Although one might think that transport companies either will train their staff to maintain and repair electric trucks or truck manufacturers and independent service stations will offer maintenance and repair services in order to prevent the loss of customers, a survey revealed that customers are concerned about a “lack and high cost of efficient manufacturer support in case repair is needed.”<sup>468</sup> The utility function needs to include the factor service station availability, because it is reasonable to think that customers do not see electric trucks as an equivalent alternative to conventional diesel trucks because of a lack of dealerships that have maintenance capabilities.<sup>469</sup> This is subsumed under the title service station availability. The purchase probability will diminish if customers believe that a potential breakdown cannot be resolved quickly due to a “lack of efficient and competitive manufacturer support.”<sup>470</sup> The availability of service for the incumbent diesel truck (100%) is taken as a reference value. The uptake of service station availability of the new drivetrain technologies is modelled exogenously and gradually approaches 100 percent by the manufacturers’ and independent garages’ investments. Service station availability is entered as a natural logarithm transformation to account for the declining marginal utility of service station availability and is given in percent.

$$\Delta V_i = \beta_9 * \ln(SA_i * 100) \quad ( 45 )$$

### **Parameters which are not included in the utility function**

The fleet size could have been added to the utility function to account for the assumptions that truck customers with higher fleet sizes put less emphasis on range and recharging time of electric vehicles, as they can complete high-mileage transport orders with the diesel trucks in their fleet and can schedule the deployment and thus the recharging slots of electric trucks in a more flexible way.<sup>471</sup> Furthermore, it is reasonable to believe that larger firms are financially more robust and therefore more

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<sup>468</sup> Quak et al. (2016), p. 1515

<sup>469</sup> Klemick et.al. (2015), p. 161

<sup>470</sup> Quak et al. (2016), p. 1509

<sup>471</sup> Schulz et al. (2012), p. 87

willing to burden the high upfront cost of electric trucks.<sup>472</sup> A survey of Bain & Company found out that the new sales price is less important for larger fleets.<sup>473</sup> But a study of CE Delft, which investigated whether differently sized companies face different barriers, could not conclude that very small transport companies have further difficulties in financing new vehicles for their fleet.<sup>474</sup> However, the reason for this was that only a few small companies responded to the questionnaire. A study of the International Energy Agency about the future of trucks mentions liquidity constraints as a barrier to the adoption of more efficient technologies for smaller firms.<sup>475</sup> A further assumption is that firms with a higher fleet size tend to put greater emphasis on corporate responsibility and therefore on the green image of their trucks.<sup>476</sup>

However, the fleet size variable has not been included, as it was not possible to determine the weight for fleet size from the literature. As the characteristics of decision makers' are not included in the utility function, the Multinomial Logit Model is used in this dissertation instead of the Conditional Logit Model.

The payload is also not included in the utility function, as weight is mostly not the limiting factor in urban freight transport and it can be expected that the legislative weight threshold will be raised. On average, only 59 percent of the loading capacity of heavy goods vehicles is used in urban freight transport in London.<sup>477</sup> Furthermore, the calculation of weight changes in chapter 2.3.2 revealed that the weight increase of 190 kg of battery electric trucks is on an acceptable level. Fuel cell electric trucks are even lighter compared with conventional diesel trucks. Noise emissions are also not included, as zero emission vehicles (ZEVs) are not excluded from the Lorry Control Scheme yet. A survey conducted with transport companies showed that there is no significant difference between electric trucks and conventional diesel trucks regarding the criteria safety and reliability.<sup>478</sup> Therefore, these criteria are also not included in the utility function. Truck performance is ranked as one of the most important purchase criteria by truck operators.<sup>479</sup> Some survey participants reported that electric trucks "have an exclusive advantage of excellent acceleration and high torque, are

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<sup>472</sup> Baster et al. (2014), p. 26

<sup>473</sup> Gnamm, J. and Lundgren, J. (2016), p. 2

<sup>474</sup> Aarnink et al. (2012), p. 56

<sup>475</sup> Teter et al. (2017), p. 39

<sup>476</sup> Jenkins, A. (2017), URL see Bibliography

<sup>477</sup> Gota, S. and Wang, B. (2017), p. 20

<sup>478</sup> Quak et al. (2016), p. 1513

<sup>479</sup> Gnamm, J. and Lundgren, J. (2016), p. 2

comfortable to drive, and fast and flexible in urban traffic.”<sup>480</sup> It is therefore not possible to include truck performance as a differentiating factor between truck types.

The resale value of a truck is a decisive factor in the truck purchase decision. The crucial factor in determining the resale value of an electric truck is the battery condition. For a potential buyer of the used truck, the question will inevitably arise whether the electric truck will be operational in the intended holding period or a battery replacement will be needed. This problem can be solved by determining the battery health with “advanced software and other telematics”.<sup>481</sup> To this date, there is simply no experience regarding the resale value of electric trucks yet. A battery reaches the end of its useful life for automotive applications when the capacity reaches 80 percent of its initial value. In 2013, batteries were able to withstand 1,000-2,000 deep discharges, which correspond to a battery life of about six years.<sup>482</sup> However, technological progress will increase the number of possible charging cycles and thus make battery replacement during the service life of a distribution vehicle obsolete in the future. A study from Fraunhofer IAO states that battery manufacturers can guarantee 2,000 charging cycles for automotive applications, which equals a mileage of 400,000 to 600,000 km.<sup>483</sup> BYD goes even further and guarantees 5,000 charging cycles or a vehicle operation of 14 years if the vehicle is charged every day.<sup>484</sup> In this case, the urban delivery truck with an annual mileage of 40,000 km and a service life of 10 years would not need a battery replacement. However, the improvement of the battery technology and costs can create another problem. The expectation that battery technologies and costs will decline combined with an unknown resale value of battery electric trucks can lead to a situation, in which truck customers postpone the purchase decision of battery electric trucks.<sup>485</sup> In this dissertation, it is assumed that a battery replacement is not necessary within the service life of a truck. As the resale values of electric trucks are still unknown and will be determined by market forces<sup>486</sup>, it is assumed that they are on a comparable level with the resale value of diesel trucks. This is supported by the general low appreciation of fuel efficiency in the used vehicle market. Buyers of used vehicles may not want to pay more for fuel-efficient trucks,

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<sup>480</sup> Nesterova, N. and Quak, H. (2015), p. 19

<sup>481</sup> Electrification Coalition (2010), p. 84

<sup>482</sup> Pelletier et al. (2014), p. 5

<sup>483</sup> Raiber et al. (2014), p. 36

<sup>484</sup> BYD, p. 2

<sup>485</sup> Nesterova, N. and Quak, H. (2015), p. 43

<sup>486</sup> Electrification Coalition (2010), p. 85

which would give the first buyers of new vehicles the chance to recover the higher investment.<sup>487</sup> Given this uncertainty, resale value has also not been included in the utility function. Although the battery can still be employed in operations like balancing intermittent renewables after the end of its useful life for automotive applications, the revenue from the sale of the battery on the secondary battery market was not considered.<sup>488</sup> Similarly, the future residual value of diesel trucks might be difficult to estimate in the light of an increase of political measures in cities like the introduction of a ban for highly polluting diesel trucks from city centres or the introduction of congestion charges.

The level of Vehicle Excise Duty (VED) depends on the vehicle's tax band. The owner of a rigid diesel truck with two axles and a gross vehicle weight of 12 t must pay £200 per year, which corresponds to €227. Battery electric trucks are exempt from this annual tax.<sup>489</sup> Tax costs are also not included in the utility function.

As noted earlier, the operator of a diesel truck not meeting the Euro 4 standard has to pay a congestion charge of £11.50 if he drives into the Congestion Charge Zone (CCZ) in London. With the introduction of the Ultra Low Emission Zone (ULEZ), this charge will rise considerably to £100 for operators of diesel trucks not meeting Euro 6 standard. Assuming that the operator delivers goods into the Congestion Charge Zone on 300 days per year and does not meet the required standards, he would face additional annual costs of £3,450 at this point and £30,000 with the implementation of the Ultra Low Emission Zone. The congestion charge costs are not included in the utility function, as we compare the electric trucks with a technologically up-to-date diesel truck meeting Euro 6 standard. Insurance Cost differentials between diesel trucks and battery electric trucks are not considered in this dissertation, as comparative figures do not exist, and the actual amount of insurance costs depends on transport company-specific factors.

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<sup>487</sup> Environmental Protection Agency and Department of Transportation (2015), p. 8-5

<sup>488</sup> Baster et al. (2014), p. 34

<sup>489</sup> Gov.uk (2017), p. 1

### **Definition of utility functions**

The product attributes price, fuel and maintenance and repair costs, range and infrastructure and service station availability are identical for all the alternatives, which makes them generic variables. The coefficients  $\beta$  are the same over all vehicle alternatives. The variable charging time is specific to plug-in hybrid electric vehicles and battery electric vehicles, whereas the variable refueling time is specific to diesel vehicles, plug-in hybrid electric vehicles and fuel cell electric vehicles. The variable “CO<sub>2</sub> emissions” is also alternative specific, as CO<sub>2</sub> emissions are only emitted by diesel vehicles and plug-in hybrid electric vehicles on a tank-to-wheel basis.

### **Utility Function of Diesel Truck**

$$U_{ICEV} = \beta_{ICEV,0} + \beta_1 * Price_{ICEV} + \beta_2 * c_{en,ICEV} + \beta_3 * c_{mr,ICEV} + \beta_4 * \ln(R_{ICEV}) + \beta_5 * CO_{2,ICEV} + \beta_6 * T_{r,ICEV} + \beta_8 * \ln(IA_{ICEV}) + \beta_9 * \ln(SA_{ICEV}) + \epsilon_{ICEV} \quad (46)$$

### **Utility Function of Plug-In Hybrid Electric Truck**

$$U_{PHEV} = \beta_{PHEV,0} + \beta_1 * Price_{PHEV} + \beta_2 * c_{en,PHEV} + \beta_3 * c_{mr,PHEV} + \beta_4 * \ln(R_{PHEV}) + \beta_5 * CO_{2,PHEV} + \beta_6 * T_{r,PHEV} + \beta_7 * T_{c,PHEV} + \beta_8 * \ln(IA_{PHEV}) + \beta_9 * \ln(SA_{PHEV}) + \epsilon_{PHEV} \quad (47)$$

### **Utility Function of Battery Electric Truck**

$$U_{BEV} = \beta_{BEV,0} + \beta_1 * Price_{BEV} + \beta_2 * c_{en,BEV} + \beta_3 * c_{mr,BEV} + \beta_4 * \ln(R_{BEV}) + \beta_7 * T_{c,BEV} + \beta_8 * \ln(IA_{BEV}) + \beta_9 * \ln(SA_{BEV}) + \epsilon_{BEV} \quad (48)$$

### **Utility Function of Fuel Cell Electric Truck**

$$U_{FCEV} = \beta_{FCEV,0} + \beta_1 * Price_{FCEV} + \beta_2 * c_{en,FCEV} + \beta_3 * c_{mr,FCEV} + \beta_4 * \ln(R_{FCEV}) + \beta_6 * T_{r,FCEV} + \beta_8 * \ln(IA_{FCEV}) + \beta_9 * \ln(SA_{FCEV}) + \epsilon_{FCEV} \quad (49)$$

In this dissertation, a constraint is placed on the alternative specific constant. This is done to create differences in the utility between the alternatives, as otherwise, estimation would not be possible. Here, the alternative specific constant of the diesel truck is set to zero ( $\beta_{ICEV,0}=0$ ). The parameters of the other truck alternatives are interpreted as preference differences relative to the diesel truck alternative.

The systematic part of the utility function is defined as:

### **Systematic Part of the Utility Function of Diesel Truck**

$$U_{ICEV}-\varepsilon_{ICEV} = V_{ICEV} = \beta_{ICEV,0} + \beta_1 * Price_{ICEV} + \beta_2 * c_{en,ICEV} + \beta_3 * c_{mr,ICEV} + \beta_4 * \ln(R_{ICEV}) + \beta_5 * CO_{2,ICEV} + \beta_6 * T_{r,ICEV} + \beta_8 * \ln(IA_{ICEV}) + \beta_9 * \ln(SA_{ICEV}) \quad (50)$$

### **Systematic Part of the Utility Function of Plug-In Hybrid Electric Truck**

$$U_{PHEV}-\varepsilon_{PHEV} = V_{PHEV} = \beta_{PHEV-ICEV,0} + \beta_1 * Price_{PHEV} + \beta_2 * c_{en,PHEV} + \beta_3 * c_{mr,PHEV} + \beta_4 * \ln(R_{PHEV}) + \beta_5 * CO_{2,PHEV} + \beta_6 * T_{r,PHEV} + \beta_7 * T_{c,PHEV} + \beta_8 * \ln(IA_{PHEV}) + \beta_9 * \ln(SA_{PHEV}) \quad (51)$$

### **Systematic Part of the Utility Function of Battery Electric Truck**

$$U_{BEV}-\varepsilon_{BEV} = V_{BEV} = \beta_{BEV-ICEV,0} + \beta_1 * Price_{BEV} + \beta_2 * c_{en,BEV} + \beta_3 * c_{mr,BEV} + \beta_4 * \ln(R_{BEV}) + \beta_7 * T_{c,BEV} + \beta_8 * \ln(IA_{BEV}) + \beta_9 * \ln(SA_{BEV}) \quad (52)$$

### **Systematic Part of the Utility Function of Fuel Cell Electric Truck**

$$U_{FCEV}-\varepsilon_{FCEV} = V_{FCEV} = \beta_{FCEV-ICEV,0} + \beta_1 * Price_{FCEV} + \beta_2 * c_{en,FCEV} + \beta_3 * c_{mr,FCEV} + \beta_4 * \ln(R_{FCEV}) + \beta_6 * T_{r,FCEV} + \beta_8 * \ln(IA_{FCEV}) + \beta_9 * \ln(SA_{FCEV}) \quad (53)$$

The choice probabilities for the four truck alternatives are:

### **Choice Probability of Diesel Truck**

$$P(\text{ICEV}) = \frac{\exp^{V_{\text{ICEV}}}}{\exp^{V_{\text{ICEV}}} + \exp^{(V_{\text{PHEV}} + W_{\text{EV}})} + \exp^{(V_{\text{BEV}} + W_{\text{EV}})} + \exp^{(V_{\text{FCEV}} + W_{\text{EV}})}} \quad (54)$$

### **Choice Probability of Plug-In Hybrid Electric Truck**

$$P(\text{PHEV}) = \frac{\exp^{(V_{\text{PHEV}} + W_{\text{EV}})}}{\exp^{V_{\text{ICEV}}} + \exp^{(V_{\text{PHEV}} + W_{\text{EV}})} + \exp^{(V_{\text{BEV}} + W_{\text{EV}})} + \exp^{(V_{\text{FCEV}} + W_{\text{EV}})}} \quad (55)$$

### **Choice Probability of Battery Electric Truck**

$$P(\text{BEV}) = \frac{\exp^{(V_{\text{BEV}} + W_{\text{EV}})}}{\exp^{V_{\text{ICEV}}} + \exp^{(V_{\text{PHEV}} + W_{\text{EV}})} + \exp^{(V_{\text{BEV}} + W_{\text{EV}})} + \exp^{(V_{\text{FCEV}} + W_{\text{EV}})}} \quad (56)$$

### **Choice Probability of Fuel Cell Electric Truck**

$$P(\text{FCEV}) = \frac{\exp^{(V_{\text{FCEV}} + W_{\text{EV}})}}{\exp^{V_{\text{ICEV}}} + \exp^{(V_{\text{PHEV}} + W_{\text{EV}})} + \exp^{(V_{\text{BEV}} + W_{\text{EV}})} + \exp^{(V_{\text{FCEV}} + W_{\text{EV}})}} \quad (57)$$

The choice probabilities of the truck types represent the market shares of these truck types.<sup>490</sup> The probability of choosing a truck type and thus its market share increases with improving product characteristics in the utility function. It is assumed that the parameters  $\beta$  do not change throughout the simulation period.

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<sup>490</sup> Calfee, J.E. (1985), p. 289

### 3.7 PARAMETER WEIGHTS FROM LITERATURE

The initial intention was to convince transport companies from the Road Haulage Association or the Freight Transport Association in the United Kingdom of participating in an online survey. However, the low expected rate of return from the online survey would not have guaranteed reliable parameter estimation. For this reason, the dissertation uses parameter weights obtained from the literature. Discrete choice experiments in the research area of electric mobility have been done primarily for passenger cars so far. The parameters derived from a study on the choice behaviour of car customers will not perfectly reflect the choice behaviour of truck customers, as the purchase behaviour of a truck customer is different from the purchase behaviour of a passenger car customer. Nevertheless, as the same or similar vehicle attributes are included in the utility functions of car and truck customers, and these customer types probably only differ in the parameter weights of the utility function, the parameter weights from car studies may be used in the absence of truck-specific survey data. The parameter weights have been obtained from the study by Hackbarth and Madlener (see Table 8) for this dissertation.<sup>491</sup> Truck customers might give a different weight to the parameters of the utility function. To account for this fact, the weights for selected parameters will be adapted in the scenario analysis in chapter 5. As the parameter weight for maintenance and repair costs was not given, it has been defined by expert judgement. Given the fact that maintenance and repair costs of trucks make a smaller portion of the TCO than energy costs, the parameter of maintenance and repair costs has been reduced to half of the energy costs parameter weight. What characterizes good models is the inclusion of all variables that affect the modelling outcome. From a scientific point of view, it is more favorable to estimate the parameter values by expert judgments than ignoring the variables due to an absence of data.<sup>492</sup> The parameter weight for refuelling time has been incorporated into the utility function without change. The weight of the parameter service station availability is set to 0.1.

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<sup>491</sup> Hackbarth, A. and Madlener, R. (2016), p. 96

<sup>492</sup> Sterman, J. D. (2002), p. 523

<u>Variable</u>	<u>Parameter</u>	<u>Weights</u>	<u>Expert judgement</u>
PHEV	$\beta_{\text{PHEV},0}$	-0.0910	
BEV	$\beta_{\text{BEV},0}$	-0.2155	
FCEV	$\beta_{\text{FCEV},0}$	-0.4227	
Weight Purchase Price [1/€]	$\beta_1$	-0.0519	
Weight Energy Costs per 100 km [1/€]	$\beta_2$	-0.0480	
Weight Maintenance and Repair Costs per 100 km [1/€]	$\beta_3$		-0.024
Weight Driving Range (logarithmic) [1/km]	$\beta_4$	0.4939	
Weight CO <sub>2</sub> emissions (logarithmic) [-]	$\beta_5$	-0.0489	
Weight Refuelling Time [1/min]	$\beta_6$	-0.0043	
Weight Recharging Time (logarithmic) [1/min]	$\beta_7$	-0.0651	
Weight Infrastructure Availability (logarithmic) [-]	$\beta_8$	0.2203	
Weight Service Station Availability (logarithmic) [-]	$\beta_9$		0.1

Table 8 Parameter weights used in the utility functions

The parameter weights have the expected signs:

- The lower the purchase price of a truck, the higher its purchase probability
- The lower the energy costs of a truck, the higher its purchase probability
- The lower the maintenance and repair costs of a truck, the higher its purchase probability
- The higher the driving range of a truck, the higher its purchase probability
- The lower the CO<sub>2</sub> emissions of a truck, the higher its purchase probability
- The lower the recharging/refuelling time of a truck, the higher its purchase probability
- The higher the infrastructure availability for a truck, the higher its purchase probability
- The higher the service station availability for a truck, the higher its purchase probability

## 4. DIFFUSION OF ELECTRIC TRUCKS IN URBAN FREIGHT TRANSPORT

In his seminal work *Diffusion of Innovations*, Everett Rogers defines innovation diffusion as the “process by which (1) an innovation (2) is communicated through certain channels (3) over time (4) among the members of a social system.”<sup>493</sup> The four main elements found in all innovation diffusion studies are therefore the innovation, which is represented by the electric trucks in this case, the social system, which is represented by the truck customers, time and the communication channels. The communication channels comprise mainly the marketing efforts of manufacturers, journals, fairs and word-of-mouth communication between customers. According to Rogers, there are five stages through which an individual passes through in his innovation-decision process, namely knowledge, persuasion, decision, implementation, and confirmation.<sup>494</sup> Thus, a customer will only decide to use the innovation if he gains awareness of its existence and is certain about its benefits. Otherwise, he will decide to reject it. The uncertainty about the benefits of the innovation is reduced by communication between members of the social system. The innovation is evaluated regarding its five attributes relative advantage, compatibility, complexity, trialability, and observability.<sup>495</sup> The higher the relative advantage, compatibility, trialability and observability of an innovation, the higher will be its rate of adoption. Complexity has the reverse effect on the rate of adoption of an innovation. The confirmation stage in the innovation-decision process helps to determine whether the innovation meets the expectations and therefore is not used anymore if it does not meet them. Rogers classified the adopters depending on their innovativeness into the categories innovators, early adopters, early majority, late majority, and laggards. “The adoption of an innovation usually follows a normal, bell-shaped curve when plotted over time on a frequency basis. If the cumulative number of adopters is plotted, the result is an S-shaped curve.”<sup>496</sup>

The most prominent diffusion model in marketing research is the Bass Model, which tries “to forecast how many adoptions of a new product will occur at future time

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<sup>493</sup> Rogers, E. (2003) p. 11

<sup>494</sup> Ibid., p. 20

<sup>495</sup> Ibid., p. 222

<sup>496</sup> Ibid., p. 272

periods, or on the basis of pilot launches of a new product, or from managerial judgments made on the basis of the diffusion history of analogous products.”<sup>497</sup> There are two communication channels which drive the diffusion of an innovation. The diffusion process is initiated by mass media communication, by which innovators are persuaded to adopt the innovation (external influence) and word-of-mouth communication between innovators and imitators (internal influence). The Bass Model is a combination of the Fourt/Woodlock Model, which attributes the diffusion process to mass media communication (External Influence Model) and the Mansfield Model in which the diffusion is only affected by previous buyers (Internal Influence Model).<sup>498</sup> Therefore the Bass Model is also called Mixed-Influence-Model:

$$\frac{dN(t)}{dt} = \left( a + b \cdot \frac{N(t)}{M} \right) * [M - N(t)] \quad ( 58 )$$

- a: Innovation Parameter
- b: Imitation Parameter
- M: Market Potential
- $\frac{N(t)}{M}$ : Market Saturation Level
- [M-N(t)]: Remaining Market Potential

The two main properties of the Bass Model are that the point of inflection is at 50 percent of the market potential and that the diffusion curve is symmetric. However, not every diffusion curve follows the same pattern. For example, the curves may differ in slope and asymptote, representing different paced forms of diffusion.<sup>499</sup> Various types of diffusion models have been developed to circumvent the limitations of the Mixed-Influence diffusion model regarding the point of inflection and the symmetry of the curve.<sup>500</sup>

Growth models are often criticized for their retrospective assessment of innovation diffusion and their inability to properly forecast the uptake of innovations in the market.

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<sup>497</sup> Rogers, E. (2003) p. 209

<sup>498</sup> Mahajan et al. (1991), p. 128f.

<sup>499</sup> Mahajan, V. and Peterson, R. (1985), p. 8

<sup>500</sup> Ibid., p. 29

“Parameter estimation for diffusion models is primarily of historical interest; by the time sufficient observations have developed for reliable estimation, it is too late to use the estimates for forecasting purposes.”<sup>501</sup> What is needed instead is a model which allows the estimation of market growth without having to know in advance what the maximum market potential will be. Thereby firms “can decide whether the market will be big enough to justify entry and plan strategy for capacity acquisition, pricing, marketing, and so on.”<sup>502</sup> In the next chapter, a methodology will be presented, that is capable of simulating the market development of innovative products and thus can be used as a tool to support product management decisions.

## 4.1 SYSTEM DYNAMICS THEORY

There are different stakeholders in the trucking business like manufacturers, transport companies, fuel suppliers and governmental authorities, which have particular interests and take decisions based on these interests. The trucking industry is inherently very complex due to the huge variety of duty cycles and truck classifications. In addition to that, the customer base within these different duty cycles is very fragmented into different economic segments and company sizes. This makes it difficult for governmental authorities to define one-size-fits-all regulations for the whole trucking business.<sup>503</sup> But to achieve climate and sustainability goals, it is inevitable to introduce regulatory measures like CO<sub>2</sub> emissions limits to curb the greenhouse gas output of freight transport. It will be interesting to watch how the truck manufacturers will respond to these challenges. Truck customers play an important role in achieving climate goals, as their purchase decisions finally determine the success of electric drivetrain technologies in the market as an option to tackle CO<sub>2</sub> emissions. Governmental authorities might try to channel the purchase behaviour of truck customers towards electric drivetrain technologies by introducing low emission zones, giving subsidies or supporting the construction of a minimum number of battery charging points and hydrogen refuelling stations to support market uptake of electric trucks. Fuel suppliers will not be willing to invest in charging points or hydrogen

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<sup>501</sup> Mahajan et al. (1991), p. 140

<sup>502</sup> Sterman, J. D. (2000), p. 327

<sup>503</sup> Baster et al. (2014), p. 21

refuelling stations if there is no refuelling demand, while customers might rate electric trucks negatively as long as there is no sufficient infrastructure coverage. These particular interests of stakeholders and their interconnectedness make clear that it is important to consider the whole system.<sup>504</sup> System Dynamics is a tool that has been developed to understand such dynamic and complex systems.<sup>505</sup> For example, an increase in charging points coverage will increase the attractiveness of battery electric trucks and eventually lead to a higher market share of battery electric trucks, which in turn will attract more fuel suppliers to invest in charging infrastructure. A higher market share of battery electric trucks will help manufacturers to decrease production costs due to economies of scale, which in turn increases the attractiveness and the market share of battery electric trucks even further. A system in which the input is changed based on the output is called a feedback system.<sup>506</sup> The examples above are positive feedback loops, as they generate further growth, whereas negative feedback loops are goal-seeking.<sup>507</sup> There are several steps, which need to be taken step by step to create a System Dynamics model. These are:

- “Identify the problem and formulate the mental model in the form of a verbal description (problem identification/conceptualisation) and develop a dynamic hypothesis to account for problematic behaviour in terms of causal loop diagrams and stock and flow structure of the system.
- Create basic structure of the causal diagram from the verbal model.
- Augment causal loop diagrams into system dynamics flow diagrams.
- Translate the System Dynamics flow diagrams into STELLA or VENSIM or a set of simultaneous difference equations.
- Estimate the parameters.
- Validate the model, analyse the sensitivity and analyse the policy.
- Application of the model”.<sup>508</sup>

It is important to bear in mind that all models are wrong and that these models are a reflection of the limitations of our knowledge.<sup>509</sup> Therefore, System Dynamics models

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<sup>504</sup> Bala et al. (2017), p. 4

<sup>505</sup> Ibid., p. 15

<sup>506</sup> Ibid., p. 6

<sup>507</sup> Ibid.

<sup>508</sup> Ibid., p. 12

<sup>509</sup> Sterman, J. D. (2002), p. 521

cannot be validated regarding truthfulness.<sup>510</sup> But System Dynamics models can be validated regarding their “soundness and usefulness”.<sup>511</sup> The identification of the problem starts with the definition of the problem and its boundaries and is concluded with the setting of objectives.<sup>512</sup> It is critical to ensure that all factors that are needed to solve the research problem are taken into account. Furthermore, the relationships between these factors have to be described, what is usually done with a basic block or sectorial diagram (see Figure 11).<sup>513</sup>

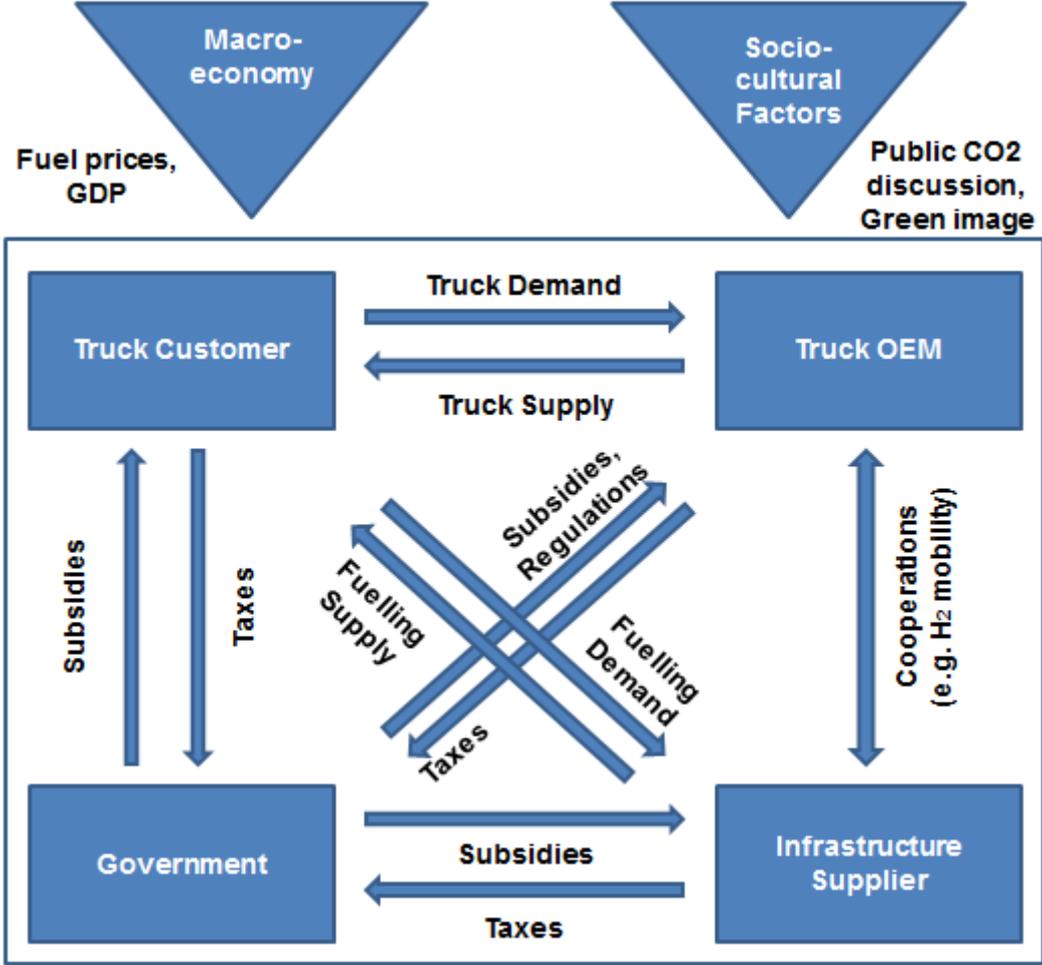


Figure 11 Sectorial diagram

The system boundary separates exogenous variables from endogenous variables.<sup>514</sup> An example for an exogenous variable in the context of this dissertation is fuel price, which is not determined within the system’s boundaries, whereas battery production

<sup>510</sup> Sterman, J. D. (2002), p. 521  
<sup>511</sup> Bala et al. (2017), p. 23  
<sup>512</sup> Ibid., p. 17  
<sup>513</sup> Ibid., p. 18  
<sup>514</sup> Ibid., p. 21

cost is an endogenous variable, as it decreases with increasing battery production experience.

The process of building up a System Dynamics model continues with the description of the feedback structure between the variables within the systems with so-called causal-loop-diagrams.<sup>515</sup> The relationship between variables can be allocated either to positive or negative cause-effect relationships. A cause-effect relationship is positive if an increase or decrease in one variable leads to a change in the other variable in the same direction.<sup>516</sup> A negative cause-effect relationship, however, is characterized by an inverse relationship, where an increase in one variable leads to a decrease in the other variable and vice versa.<sup>517</sup> A feedback loop may have several such cause-effect relationships. It has already been stated that positive feedback loops are reinforcing and generate growth and negative feedback loops are goal-seeking. To determine the sign of a loop, one has to count the number of negative cause-effect relationships.<sup>518</sup>

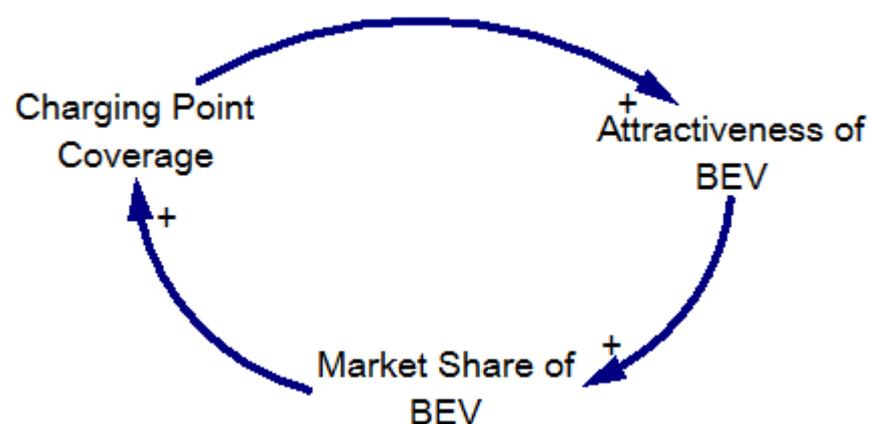


Figure 12 Example for a positive feedback loop

“If there are an even numbers of negative relationships in total in a feedback loop, then the loop is positive; if there are odd numbers of negative relationships, the loop is negative.”<sup>519</sup> In the example above (see Figure 12), higher charging point coverage will increase the attractiveness of battery electric trucks and lead to a higher market share of battery electric trucks. This, in turn, will attract infrastructure investors and

<sup>515</sup> Bala et al. (2017), p. 21

<sup>516</sup> Ibid., p. 37

<sup>517</sup> Ibid., p. 37f.

<sup>518</sup> Ibid., p. 39

<sup>519</sup> Ibid.

eventually result in an expansion in infrastructure coverage. The feedback loop is positive, as the cause-effect relationships between these variables are positive. Following the causal-loop diagrams, the stock-flow diagrams are defined. The following example of vehicle stock shall illustrate how stock-flow diagrams are built up. The stock describes the current state of a system and is represented here by the vehicle stock.<sup>520</sup> A stock does not necessarily have to be of a physical nature, but can also be the accumulation of knowledge for example.<sup>521</sup> The net flow gives information about “the rate of change of the stock.”<sup>522</sup> Inflows are increasing the level of the stock, whereas outflows are decreasing it.<sup>523</sup> Concerning the example above, inflows are represented by sales of vehicles per time unit and outflows by discards of vehicles per time unit. A “first-order finite difference equation”<sup>524</sup> can mathematically describe the increase in the level of a stock:

$$\text{Vehicle Stock (t)} = \text{Vehicle Stock}(t_0) + \int_{t_0}^t (\text{Sales}(t) - \text{Discards}(t)) \quad ( 59 )$$

The Euler’s method is used by the software to solve the differential equations. The next steps in System Dynamics modelling are parameter estimation and sensitivity analysis, model validation and use and scenario analysis. The definition of all parameters, which are used in the stock-flow diagrams, will be performed in the next chapter together with sensitivity analysis for the most important parameters.

## 4.2 SYSTEM DYNAMICS MODEL

The System Dynamics model comprises all the elements of the sectoral diagram. These elements are the truck customers, truck manufacturers, infrastructure suppliers, and the government. Furthermore, exogenous variables like the diesel price

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<sup>520</sup> Bala et al. (2017), p. 54

<sup>521</sup> Ibid., p. 55

<sup>522</sup> Ibid.

<sup>523</sup> Ibid.

<sup>524</sup> Ibid., p. 59

development and the gross domestic product growth factor are taken into account. In the next chapters, these elements will be explained in detail.

#### 4.2.1 TRUCK CUSTOMER PERSPECTIVE

The actual vehicle stock rises with the sales rate and decreases with the discard rate.

$$\frac{d}{dt} F_i(t) = r_i^{\text{sales}}(t) - r_i^{\text{disc}}(t) \quad (60)$$

$F_i(t)$ : Actual stock of truck type i [Truck]

$r_i^{\text{sales}}(t)$ : Sales rate of truck type i [Truck/Year]

$r_i^{\text{disc}}(t)$ : Discard rate of truck type i [Truck/Year]

The truck type specific sales rate in year t is dependent on the choice probability of the specific truck type and the total truck demand in that year.

$$r_i^{\text{sales}}(t) = P_i(t) * D(t) \quad (61)$$

$r_i^{\text{sales}}(t)$ : Sales rate of truck type i [Truck/Year]

$P_i(t)$ : Purchase probability of truck type i [-]

$D(t)$ : Total truck demand [Truck/Year]

The choice probability of a specific truck type is a function of its attributes and the weight parameters, which determine the importance of these attributes in the purchase decision of the truck customer.

Total sales rate is the sum of the sales rates of all truck types.

$$r_{\text{total}}^{\text{sales}}(t) = \sum_i r_i^{\text{sales}}(t) \quad (62)$$

The approach of Thies et al. is applied to determine the discard rate of trucks. They calculate the discard rate of trucks as the ratio of the vehicle stock and the average vehicle service life, after which the vehicle is replaced.<sup>525</sup>

$$r_i^{\text{disc}}(t) = \frac{F_i(t)}{\tau} \quad (63)$$

$r_i^{\text{disc}}(t)$ : Discard rate of truck type  $i$  [Truck/Year]

$F_i(t)$ : Actual stock of truck type  $i$  [Truck]

$\tau$ : Average service life of truck type  $i$  [Year]

However, Thies et al. point out that this approach only “gives an approximation of the particular scrappage rates because the composition of the vehicle stock is not stationary.”<sup>526</sup> Based on the calculations in the chapter “Urban-Delivery and the UK Freight Market”, the total stock of rigid trucks, which are deployed in urban transport, is assumed to be 108,409 trucks in the initial year (see Table 9). There is no distinction made between the truck types regarding durability. The average service life of an urban distribution truck is assumed to be ten years for all truck types.<sup>527</sup> At the beginning of the simulation period, the total vehicle stock consists only of diesel trucks.

The total discard rate is the sum of the discard rates of all truck types.

$$r_{\text{total}}^{\text{disc}}(t) = \sum_i r_i^{\text{disc}}(t) \quad (64)$$

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<sup>525</sup> Thies et al. (2016), p. 10

<sup>526</sup> Ibid.

<sup>527</sup> Safarianova et al. (2012), p. 9

Total Demand for new trucks is calculated as the sum of repurchases and new adoptions. As repurchases replace discarded vehicles, the total demand generated by repurchases is equivalent to the sum of discards of all drive platforms. Total Truck demand rises with new adoptions, which can be attributed to an expansion of the existing fleet from operators or transport companies appearing in the market as new customers. “The markets for medium- and heavy-duty trucks tend to expand in step with freight volume, which rises and falls in line with the gross domestic product.”<sup>528</sup> For that reason, demand from new adopters in a market grows in line with the gross domestic product (GDP) of a country.<sup>529</sup> If the gross domestic product slips into negative figures, the total number of replaced vehicles is reduced as a result of extended holding periods of trucks in an economic downturn. This is a simplified modelling approach for market sales growth. In reality, a gross domestic product growth must not necessarily lead to a proportional growth in truck sales. As delivery trucks in urban freight transport are not fully loaded, truck customers might choose to increase the loading factor of their trucks instead of buying new trucks, if the freight volume rises. Total truck demand is defined as follows:

$$D(t) = \text{MAX} * [0, r_{\text{total}}^{\text{disc}}(t) * (1 + g_{\text{GDP}})] \quad ( 65 )$$

D(t): Total truck demand [Truck/Year]

$r_{\text{total}}^{\text{disc}}(t)$ : Total discard rate of trucks [Truck/Year]

$g_{\text{GDP}}$ : Forecasted GDP growth factor [-]

According to OECD forecasts, the British Economy is going to grow with one percentage points in 2018.<sup>530</sup> Although the British Economy showed a cyclical development in the last decade, the seasonally adjusted gross domestic product index clearly shows that the British Economy grew nearly constantly over the last 20

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<sup>528</sup> Mohr et. al (2016), p. 7

<sup>529</sup> ACEA (2017), p. 33

<sup>530</sup> OECD (2017), p. 1

years.<sup>531</sup> Therefore the gross domestic product growth factor of one percent per year is used until the end of the simulation period (see Table 9). This is consistent with the forecast of an increase in road freight transport activity by 1.1 percent per year until 2050.<sup>532</sup>

		Value
The total stock of ICEVs	$F_{ICEV}(t)$	108,409 Trucks
The total stock of plug-in hybrid electric trucks	$F_{PHEV}(t)$	0
The total stock of battery electric trucks	$F_{BEV}(t)$	0
The total stock of fuel cell electric trucks	$F_{FCEV}(t)$	0
The average service life of a truck	$T$	10 years
Forecasted gross domestic product growth factor [-]	$g_{GDP}$	0.01

Table 9 Composition of the total vehicle stock in the initial year of the simulation period and gross domestic product growth factor

The following Figure 13 shows the implementation of the calculation of vehicle sales and discards and the vehicle stocks in System Dynamics.

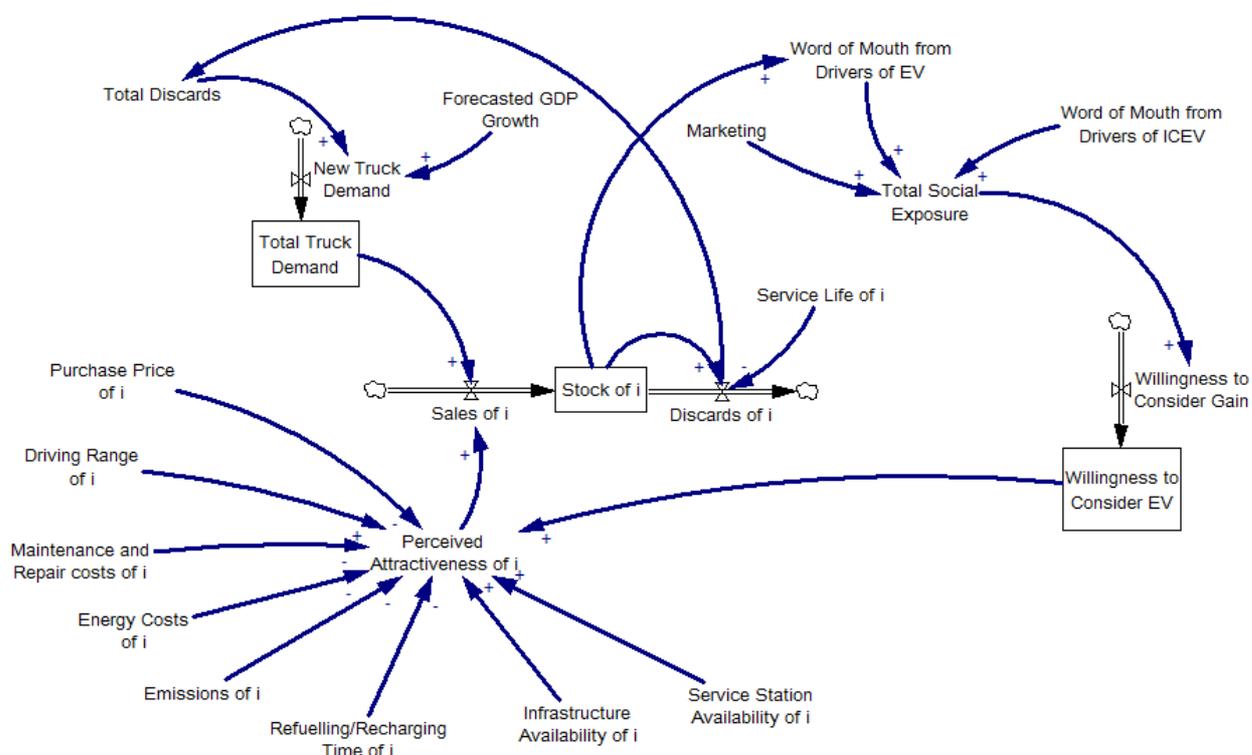


Figure 13 Calculation of vehicle sales and discards and vehicle stocks in System Dynamics

<sup>531</sup> Office for National Statistics (2017), URL see Bibliography

<sup>532</sup> European Commission (2018b), URL see Bibliography

## 4.2.2 TRUCK MANUFACTURER PERSPECTIVE

The cost-related price of electric trucks is calculated based on the cost-related price of a diesel truck by adding the costs of the alternative powertrains. This term is calculated by adding the costs for drivetrain specific components like battery, fuel cell system and subtracting the costs for the internal combustion engine and multiplying the result with the Original Equipment Manufacturer's (OEM) (1.7) surcharge factor (see Table 10). This factor accounts for the costs of research and development, vehicle integration including logistics and assembly, selling and general administration and the retail sector.<sup>533</sup> The target operating profit margin of the manufacturer  $\pi^{\text{margin}}$  is then factored into the vehicle production costs  $C_i^{\text{OEM}}$ , which results in the manufacturer's vehicle price  $\text{Price}_i^{\text{OEM}}(t)$ .

$$C_i^{\text{OEM}}(t) = c_{\text{ICEV}}(t) + (c_i^{\text{EV}}(t) - c_i^{\text{ICE}}(t)) * (\text{OEM}^{\text{sur}}) \quad (66)$$

$$\text{Price}_i^{\text{OEM}}(t) = C_i^{\text{OEM}} * (1 + \pi^{\text{margin}}) \quad (67)$$

$$c_i^{\text{EV}}(t) = c_i^{\text{EM}}(t_0) + c_i^{\text{BAT}}(t) + c_{\text{FCEV}}^{\text{FC}}(t) + c_{\text{FCEV}}^{\text{H2}}(t) + c_i^{\text{Aux}}(t) \quad (68)$$

$C_i^{\text{OEM}}(t)$ : Vehicle production cost for truck type i [€/Truck]

$\text{Price}_i^{\text{OEM}}(t)$ : Manufacturer's vehicle price of truck type i [€/Truck]

$\text{OEM}^{\text{sur}}$ : OEM surcharge factor [-]

$\pi^{\text{margin}}$ : Target operating profit margin [-]

$c_{\text{ICEV}}(t)$ : Basic diesel truck production cost [€/Truck]

<sup>533</sup> van der Slot et al. (2016), p. 118

- $c_i^{EV}(t)$ : Additional electric powertrain costs of truck type i [€/Truck]
- $c_i^{ICE}(t)$ : Production costs of the diesel engine and tank in truck type i [€/Truck]
- $c_i^{EM}(t_0)$ : Production costs of E-Motor and E-Motor control in truck type i [€/Truck]
- $c_i^{BAT}(t)$ : Production costs of battery in truck type i [€/Truck]
- $c_{FCEV}^{FC}(t)$ : Production costs of fuel cell system [€/Truck]
- $c_{FCEV}^{H2}(t)$ : Production costs of hydrogen tank [€/Truck]
- $c_i^{Aux}(t)$ : Production costs of auxiliaries in truck type i [€/Truck]

		ICEV	PHEV	BEV	FCEV
Basic truck costs	$C_{ICEV}(t)$	85155	85155	85155	85155
Fuel cell system	$c_{FCEV}^{FC}(t)$		0	0	26840
Hydrogen storage	$c_{FCEV}^{H2}(t)$		0	0	3671
Battery	$c_i^{BAT}(t)$		7800	27390	2627
E-Motor	$c_i^{EV}(t)$		1594	2458	2458
E-Motor control			310	310	310
Diesel tank	$c_i^{ICE}(t)$		0	-155	-155
Diesel engine with transmissions			0	-8840	-8840
DC/DC-Converter	$c_i^{Aux}(t)$		300	300	900
AC/DC-Converter (charger)			410	615	0
OEM surcharge factor [-]	$OEM^{sur}$		1.7		
Target operating profit margin [-]	$\pi^{margin}$		0.1		
<b>Total (with OEM surcharge factor and target operating profit margin)</b>	$Price_i^{OEM}(t)$	<b>93670</b>	<b>114290</b>	<b>137385</b>	<b>148737</b>

Table 10 Cost valuation based on the diesel truck<sup>534</sup>

<sup>534</sup> Daimler AG

From the Table 10, one can see that the battery electric truck and the fuel cell electric truck are considerably more expensive than the diesel truck, which is mainly caused by the high battery and fuel cell costs. The cost of the plug-in hybrid electric truck is lower due to lower battery cost. The battery capacity of the plug-in hybrid electric truck is 26 kWh and enables a range of approximately 30 km. The electric motor used in the plug-in hybrid electric truck has a power of 86 kW, whereas an electric motor with a power of 133 kW propels the fuel cell electric truck and the battery electric truck.<sup>535</sup> Based on a study of TU Graz on fuel-saving measures in the commercial transport sector, the maximum percentage of achievable diesel fuel consumption reduction of a 12 t truck in the distribution transport is 17 percent (see Table 11).<sup>536</sup> This value was calculated using the simulation tool VECTO and results from the implementation of a package of individual measures, which are already available on the market or which are going to be introduced in the coming years. Such measures include aerodynamic improvements like a partial fairing and a truncated rear end, low rolling resistance tyres, start/stop system, efficient auxiliaries, higher engine efficiency, lightweight, rearview camera and improvements in engine and transmission efficiency.<sup>537</sup> It is assumed that truck manufacturers have the incentive to include these fuel-saving measures into their trucks gradually over the coming years, as a CO<sub>2</sub> emissions limit with penalty payments will be introduced in 2025.

<b><u>Measures</u></b>	<b>Fuel Consumption Reduction in %</b>	<b>Costs in €</b>
Transmission and axles efficiency improvement	1.3	40
Actual low rolling resistance tyres	0.9	40
Future low rolling resistance tyres	5.7	320
Engine efficiency improvement	2.5	305
Start/Stop system	2.2	940

<sup>535</sup> Daimler AG

<sup>536</sup> Dünnebeil et al. (2015), p. 22

<sup>537</sup> Ibid., p. 22

Lightweight 200 kg	1.2	930
Efficient auxiliaries	1.6	1,900
Aerodynamic improvement	1.8	3,150
Rear view camera	0.6	4,900

Table 11 Fuel consumption reduction measures<sup>538</sup>

Aerodynamic measures and the implementation of a rearview camera to reduce air drag are not profitable within the service life of a truck.<sup>539</sup> For these reasons, they are not implemented in a diesel truck by manufacturers. The implementation of the other measures increases the price of the diesel truck by €4,475. It is assumed that the application of these measures reduces fuel consumption by 15.4 percent. The fuel consumption of the reference diesel truck, which was determined with VECTO based on the Urban Delivery Cycle, is 20.9 l per 100 km.<sup>540</sup> This means that the application of fuel-saving measures can reduce the fuel consumption of a diesel truck to approximately 17.68 l per km. The fuel consumption reduction of the diesel truck is implemented as a first-order goal-seeking process.<sup>541</sup> The adjustment time  $\tau^{\delta}$  determines how fast the maximum percentage of achievable diesel consumption reduction of 15.4 percent is approached.

$$Q_i^{\text{Diesel}}(t) = Q_i^{\text{Diesel}}(t_0) * (1 - \delta_{\text{ICEV}}(t)) \quad (69)$$

$Q_i^{\text{Diesel}}(t)$ : Diesel consumption of a truck type i [l/km\*Truck]

$Q_i^{\text{Diesel}}(t_0)$ : Diesel consumption of a truck type i in the initial year [l/km\*Truck]

$\delta_{\text{ICEV}}(t)$ : Diesel consumption reduction of the diesel truck [-]

$$\frac{d}{d(t)} \delta_{\text{ICEV}}(t) = \frac{\delta_{\text{ICEV}}^* - \delta_{\text{ICEV}}}{\tau^{\delta}} \quad (70)$$

<sup>538</sup> Dünnebeil et al. (2015), p. 175-177

<sup>539</sup> Ibid., p. 108

<sup>540</sup> Ibid., p. 175

<sup>541</sup> Thies et al. (2016), p. 9

$\bar{\delta}_{ICEV}^*$  : Maximum percentage of achievable diesel consumption reduction [-]

$\tau^{\bar{\delta}}$ : Adjustment time for diesel consumption reduction [-]

The following Table 12 lists data needed to calculate the fuel consumption reduction of a diesel truck.

Maximum percentage of achievable diesel consumption reduction [-]	$\bar{\delta}^*$	0.154
Diesel consumption of a truck in the initial year [l/km*Truck]	$Q_i^{Diesel}(t_0)$	0.209
Adjustment time for diesel consumption reduction [year]	$\tau^{\bar{\delta}}$	10

Table 12 Data for fuel consumption reduction of a diesel truck

It is assumed that “the measures with the best reduction-cost ratio are applied first, so the marginal cost to achieve further reductions increases.”<sup>542</sup> Accordingly, the transmission and axles efficiency improvement is implemented in the first place, followed by low rolling resistance tyres and engine efficiency improvement. As the implementation of these measures will be gradually over time, an adjustment factor for diesel fuel consumption is introduced. The cost increment due to fuel saving measures is implemented as a Lookup function. Lookup functions describe the relationship between an input parameter, here relative fuel consumption reduction and the output parameter costs associated with these fuel consumption reductions (see Figure 14).

$$c_i^{ICE}(t) = c_i^{ICE}(t_0) + (f(\bar{\delta}(t))) \quad (71)$$

$c_i^{ICE}(t)$ : Production costs of ICE for the truck type i [€/Truck]

$\bar{\delta}(t)$ : Diesel consumption reduction of a truck type i [-]

$f(\bar{\delta}(t))$ : Additional costs for diesel consumption reduction [€]

<sup>542</sup> Thies et al. (2016), p. 9

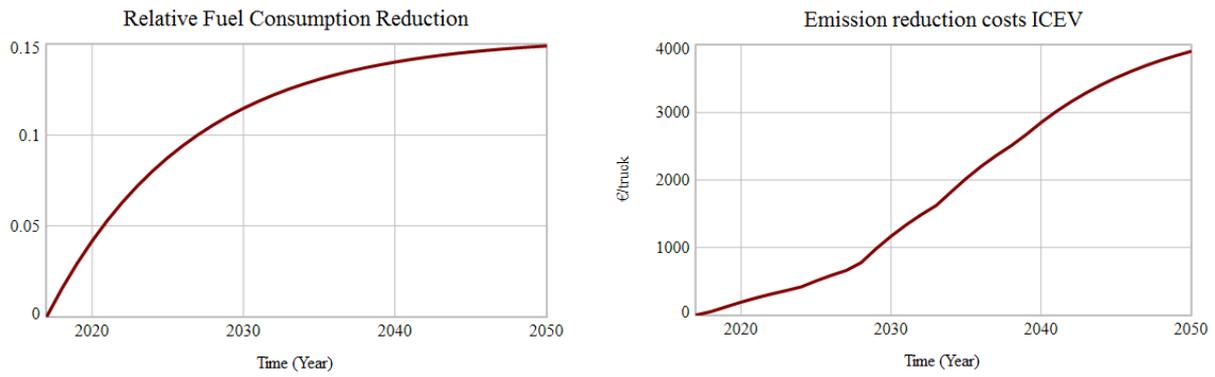


Figure 14 Relative diesel fuel consumption reduction and associated cost increase

The energy consumption of electric trucks will also improve due to high research efforts. According to den Boer et al., the energy consumption of a battery electric truck will decrease by one percent per year, whereas the energy consumption of a fuel cell electric truck will decrease by 0.83 percent per year (see Table 13).<sup>543</sup> The fuel reduction assumption of one percentage point per year for the battery electric truck is also applied for the plug-in hybrid electric truck.

$$\frac{d}{dt} Q_i^{el}(t) = Q_i^{el}(t_0) * \delta_i(t) \quad ( 72 )$$

$Q_i^{el}(t)$ : Energy consumption of truck type i [kWh/km\*Truck]

$\delta_i(t)$ : Energy consumption reduction of truck type i per year [-]

The following Table 13 lists all data needed to calculate the energy consumption reduction of electric trucks.

Energy consumption of the battery electric truck [kWh/km*Truck]	$Q_{BEV}^{el}(t_0)$	0.62
Energy consumption of the plug-in hybrid electric truck [kWh/km*Truck]	$Q_{PHEV}^{el}(t_0)$	0.62

<sup>543</sup> den Boer et al. (2013), p. 82

Energy consumption of the fuel cell electric truck [kWh/km*Truck]	$Q_{FCEV}^{el}(t_0)$	1.9
Percentage of energy consumption reduction for the battery electric truck [-]	$\delta_{BEV}(t)$ :	0.01
Percentage of energy consumption reduction for the plug-in hybrid electric truck [-]	$\delta_{PHEV}(t)$ :	0.01
Percentage of energy consumption reduction for the fuel cell electric truck [-]	$\delta_{FCEV}(t)$ :	0.0083

Table 13 Energy consumption reduction values

The energy capacity of a battery is calculated by multiplying the mass of the battery with the energy density of the battery:

$$cap_i^{BAT}(t) = m_{BAT}(t) * d_{BAT}(t) \quad ( 73 )$$

$cap_i^{BAT}(t)$ : Energy capacity of battery in truck type i [kWh/Truck]

$d_{BAT}(t)$ : Energy density of battery [kWh/kg]

$m_{BAT}(t)$ : Battery mass [kg/Truck]

The multiplication of the battery capacity with the cost of the battery per kWh results in the production costs of the battery. In the literature, the battery cost per kWh ranges from 500 \$/kWh to 180 \$/kWh. Following the approach of Teter et al., an average battery pack cost of 350 \$/kWh is used<sup>544</sup>, which approximately corresponds to 300 €/kWh with the Euro to Dollar monthly (1.17) exchange rate of August 2018.<sup>545</sup> Given a fixed battery size, the increase in battery energy density due to technological developments would automatically result in higher battery capacity and higher driving ranges. Higher driving ranges are generally welcomed, but it has to be born in mind that a higher battery capacity, in turn, leads to a higher battery cost, if the battery cost reduction due to economies of scale does not compensate the cost increase due to

<sup>544</sup> Teter et al. (2017), p. 96

<sup>545</sup> statista (2018), URL see Bibliography

higher battery capacity. Truck manufacturers could either keep the driving range on a constant level and reduce the battery size and the truck weight or increase the battery capacity and thus driving range, which would result in higher costs. Transport companies in urban freight transport might not be interested in higher driving ranges, as the battery capacity suffices to perform most transport tasks. It is therefore assumed that transport companies in urban freight transport will favour a solution that guarantees a moderate increase in driving range, but not at the expense of higher truck prices. Therefore, a maximum battery capacity is introduced, that prevents an unnecessarily high increase in driving range and thus an increase in battery cost.

$$c_i^{\text{BAT}}(t) = \text{Min} \left( c_{\text{kWh}}^{\text{BAT}}(t) * \text{cap}_i^{\text{BAT}}(t), c_{\text{kWh}}^{\text{BAT}}(t) * \text{cap}_i^{\text{maxBAT}} \right) \quad ( 74 )$$

$c_i^{\text{BAT}}(t)$ : Production costs of battery in truck type i [€/Truck]

$c_{\text{kWh}}^{\text{BAT}}(t)$ : Cost of battery per kWh capacity on pack-level [€/kWh]

$\text{cap}_i^{\text{BAT}}(t)$ : Energy capacity of battery in truck type i [kWh/Truck]

$\text{cap}_i^{\text{maxBAT}}$ : Maximum energy capacity of battery in truck type i needed [kWh/Truck]

Learning curve theory states that each doubling of experience leads to a productivity rise by a given percentage, where cumulative production commonly approximates average experience:<sup>546</sup>

$$\text{Productivity} = \text{Reference Productivity} * \left( \frac{\text{Average Experience}}{\text{Reference Experience}} \right)^c \quad ( 75 )$$

The slope of the learning curve depends on the exponent  $c$ , with  $\lambda^{\text{BAT}}$  and  $\lambda^{\text{FC}}$  as the learning rate for batteries and fuel cells respectively.<sup>547</sup>

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<sup>546</sup> Sterman, J. (2000), p. 507

<sup>547</sup> Thies et al. (2016), p. 9

$$c = \log_2(1 - \lambda^{\text{BAT}}) \quad (76)$$

The concept of the learning curve can be used to calculate the battery cost per kWh, which declines with each doubling of cumulative battery production experience.<sup>548</sup> The learning rate is 0.15 for batteries.<sup>549</sup>

$$c_{\text{kWh}}^{\text{BAT}}(t) = c_{\text{kWh}}^{\text{BAT}}(t_0) * \left( \frac{E_{\text{kWh}}^{\text{BAT}}(t)}{E_{\text{kWh}}^{\text{BAT}}(t_0)} \right)^{\log_2(1 - \lambda^{\text{BAT}})} \quad (77)$$

$c_{\text{kWh}}^{\text{BAT}}(t)$ : Cost of battery per kWh capacity on pack-level [€/kWh]

$E_{\text{kWh}}^{\text{BAT}}$ : Cumulative production experience of battery capacity [kWh]

$E_{\text{kWh}}^{\text{BAT}}(t_0)$ : Initial production experience of battery capacity [kWh]

$\lambda^{\text{BAT}}$ : Learning rate for batteries [-]

The initial phase of the diffusion of electric trucks is characterized by trials with electric trucks, in which their suitability to freight transport is assessed. Therefore, it is assumed that the initial production experience of batteries is 10,000 kWh. Trials with fuel cell trucks just started, as the example of UPS shows. Therefore, it is assumed that the initial production experience with fuel cell trucks is 1,000 kWh. For battery cost, mass production is said to occur at 100,000 battery units.<sup>550</sup> Although the learning rates in this dissertation are linked to sales of trucks in the UK, it is obvious that in reality, the learning rates will depend on the cumulative production on a global scale. However, it is assumed “that the increase in UK sales is a proportionate reflection of global trends.”<sup>551</sup> The cumulative battery production experience is defined as follows:

<sup>548</sup> Wansart, J. (2012), p. 111

<sup>549</sup> Thies et al. (2016), p. 14

<sup>550</sup> AEA (2009), p. 35

<sup>551</sup> Ibid., p. 28

$$\frac{d}{dt} E_{kWh}^{BAT}(t) = \sum_i cap_i^{BAT}(t) * r_i^{sales}(t) \quad ( 78 )$$

$E_{kWh}^{BAT}$ : Cumulative production experience of battery capacity [kWh]

$cap_i^{BAT}(t)$ : Energy capacity of battery in truck type i [kWh/Truck]

$r_i^{sales}(t)$ : Sales rate of truck type i [Truck/Year]

The battery cost development could also be implemented as an exogenous variable, as developments in the passenger vehicle segment will also influence the price reduction of truck batteries.<sup>552</sup> Another option to take into account the personal vehicle segment is increasing the cumulative production experience of battery capacity by an amount that represents the sales of electric cars. However, for reasons of simplicity, this option has not been considered in the dissertation. The range of battery and plug-in hybrid electric trucks can be extended by increasing the battery capacity or reducing the energy consumption. Due to reasons of weight and space limitation, an increase in battery capacity can only be achieved as a result of battery density growth and not by increasing the battery mass in this dissertation.

$$D_{e, i}(t) = \frac{d_{bat} * DoD_i}{Q_i^{el}(t)} \quad ( 79 )$$

$D_{e, i}$ : Electric driving range of electric truck type i [km]

$d_{bat}$ : Energy density of battery [kWh/kg]

$DoD_i$ : Depth of Discharge for truck type i [-]

$Q_i^{el}$ : Energy consumption of truck type i [kWh/km\*Truck]

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<sup>552</sup> Nykvist, B. and Nilsson, M. (2015), p. 329ff.

The current energy density of lithium-ion batteries is 0.11 kWh/kg, whereas the maximum energy density of batteries is 0.315 kWh/kg as a result of technological developments like new cathode materials. The development of the energy density of batteries is a function of cumulated battery production experience, which is an approximation of the research and development effort for battery technology improvement.<sup>553</sup> The technology specific constant is taken from Kieckhäfer.<sup>554</sup> The calculation is implemented as follows:

$$\frac{d}{dt}d_{\text{BAT}}(t)=k \cdot E_{\text{kWh}}^{\text{BAT}}(t) \cdot d_{\text{BAT}}(t) \cdot \frac{(d_{\text{BAT}}^{\text{max}}-d_{\text{BAT}}(t))}{d_{\text{BAT}}^{\text{max}}} \quad (80)$$

k: Technology specific constant [1/kWh Year]

$E_{\text{kWh}}^{\text{BAT}}$ : Cumulative battery production experience [kWh]

$d_{\text{BAT}}(t)$ : Energy density of battery [kWh/kg]

$d_{\text{BAT}}^{\text{max}}$ : Maximum energy density of battery [kWh/kg]

The following Table 14 lists all plug-in hybrid electric and battery electric truck specific data needed for the equations in this chapter.

		PHEV	BEV
Battery mass [kg/Truck]	$m_{\text{BAT}}(t)$	236	830
Energy density in the initial year [kWh/kg]	$d_{\text{BAT}}(t_0)$	0.11	
Maximum energy density [kWh/kg]	$d_{\text{BAT}}^{\text{max}}$	0.315	
Nominal energy capacity in the initial year [kWh]	$\text{cap}_i^{\text{BAT}}(t_0)$	26	91.3
The depth of Discharge factor for usable capacity [-]	DoD <sub>i</sub> :	0.7	0.9
Usable energy capacity in the initial year [kWh]		18.2	82.17

<sup>553</sup> Wansart, J. (2012), p. 108

<sup>554</sup> Kieckhäfer, K. (2013), p. 112

Cost of battery per kWh in the initial year [€/kWh]	$c_{kWh}^{BAT}(t_0)$	300	
Learning rate for batteries	$\lambda^{BAT}$	0.15	
Energy consumption [kWh/km]	$Q_i^{el}(t)$	0.62	0.62
Electric range in the initial year [km]	$R_i^{el}(t_0)$	29.35	133
Maximum installable energy capacity [kWh]	$cap_i^{maxBAT}$	40	120
Technology specific constant [1/(kWh*year)]	k	$4.85 \cdot 10^{-8}$	
Initial battery production experience [kWh]	$E_{kWh}^{BAT}(t_0)$	10,000	

Table 14 Technical values for the plug-in hybrid electric truck and the battery electric truck<sup>555</sup>

The production costs of the fuel cell system are calculated by multiplying the cost of fuel cell system per kW power with the total power of the fuel cell system in a fuel cell electric truck.

$$c_i^{FC}(t) = c_{kW}^{FC}(t) * Pow_{FCEV}^{FC}(t) \quad ( 81 )$$

$c_i^{FC}(t)$ : Production costs of fuel cell system in a fuel cell electric truck [€/Truck]

$c_{kW}^{FC}(t)$ : Cost of fuel cell system per kW power [€/kW]

$Pow_{FCEV}^{FC}(t)$ : Power of fuel cell system in a fuel cell electric truck [kW/Truck]

The total cost of fuel cell systems can be reduced by bringing down the costs of fuel cell stacks, the balance of plant (auxiliary system of fuel cell trucks grouping components like humidifier, pumps, and valves<sup>556</sup>) and high-pressure tanks. As with batteries, the production costs of fuel cells decrease due to economies of scale.<sup>557</sup> The learning rate for fuel cells is 0.2.<sup>558</sup> The fuel cell system cost of €244 per kW in the first year of the simulation period corresponds to values from the literature.<sup>559</sup>

<sup>555</sup> Daimler AG

<sup>556</sup> Bernhart et al. (2013), p. 6

<sup>557</sup> Wansart, J. (2012), p. 111

<sup>558</sup> Thies et al. (2016), p. 14

<sup>559</sup> Papageorgopoulos, D. (2016), p. 8

$$c_{kW}^{FC}(t) = c_{kW}^{FC}(t_0) * \left( \frac{E_{kW}^{FC}(t)}{E_{kW}^{FC}(t_0)} \right)^{\log_2(1-\lambda^{FC})} \quad ( 82 )$$

- $c_{kW}^{FC}(t)$ : Cost of fuel cell system per kW power [€/kW]  
 $E_{kW}^{FC}$ : Cumulative production experience for fuel cell system [kW]  
 $E_{kW}^{FC}(t_0)$ : Initial production experience of fuel cell system capacity [kW]  
 $\lambda^{FC}$ : Learning rate for fuel cell system [-]

There are different forecasts for the hydrogen tank cost in the literature.<sup>560</sup> The cost of the high-pressure tank is mainly influenced by the high prices for composite materials, which will have a different price development than that of the fuel cell system.<sup>561</sup> Therefore, the dissertation only considers economies of scale for the fuel cell system. Nevertheless, it is assumed that the hydrogen tank cost decreases to approximately €139 per kg hydrogen until 2050 (see Figure 15). The actual hydrogen tank cost is assumed to be €483 per kg hydrogen. The hydrogen tank is scaled to enable a sufficient driving range for urban freight transport. It can hold up to 7.6 kg of hydrogen. With an actual price of €483 per kg hydrogen, the tank costs €3,671 in the initial year of the simulation period.

$$c_{FCEV}^{H_2}(t) = c_{kg}^{H_2}(t) * m_{H_2} \quad ( 83 )$$

- $c_{FCEV}^{H_2}(t)$ : Production costs of hydrogen tank [€/Truck]  
 $c_{kg}^{H_2}(t)$ : Cost of hydrogen tank per kg [€/kg]  
 $m_{H_2}$ : Mass of hydrogen in tank [kg]

<sup>560</sup> Duigoi, A. and Smatti, A. (2014), p. 17877

<sup>561</sup> Körner, A. (2015), p. 14

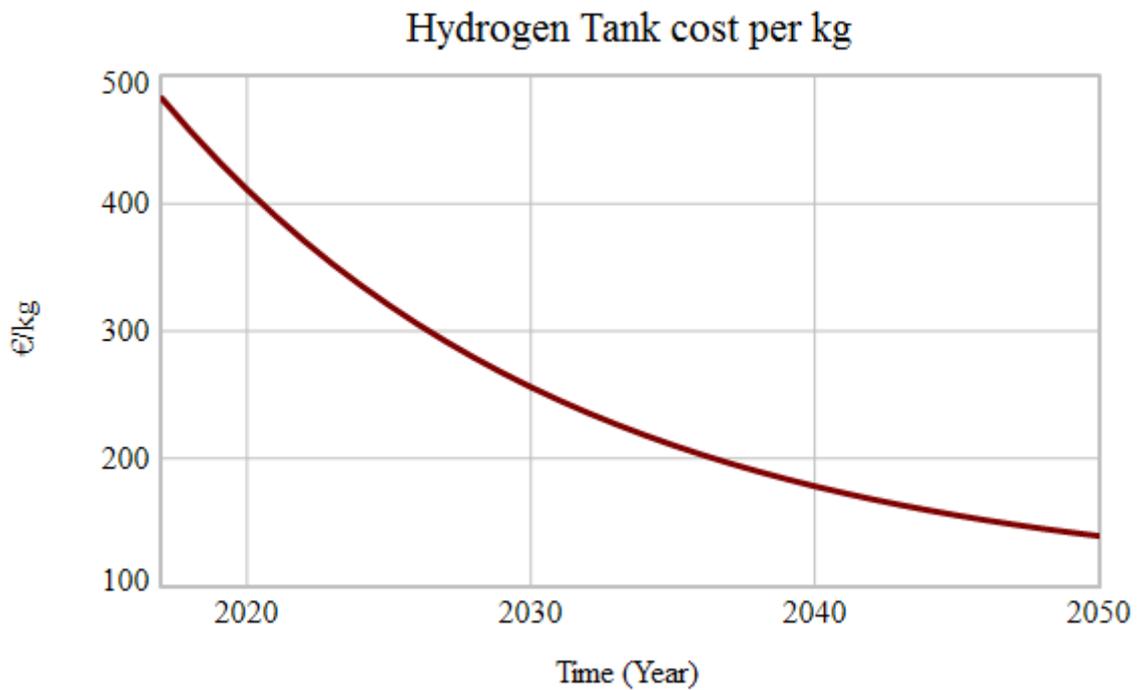


Figure 15 Hydrogen tank cost per kg hydrogen

The following Figure 16 shows the implementation of the calculation of battery electric truck production costs in System Dynamics.

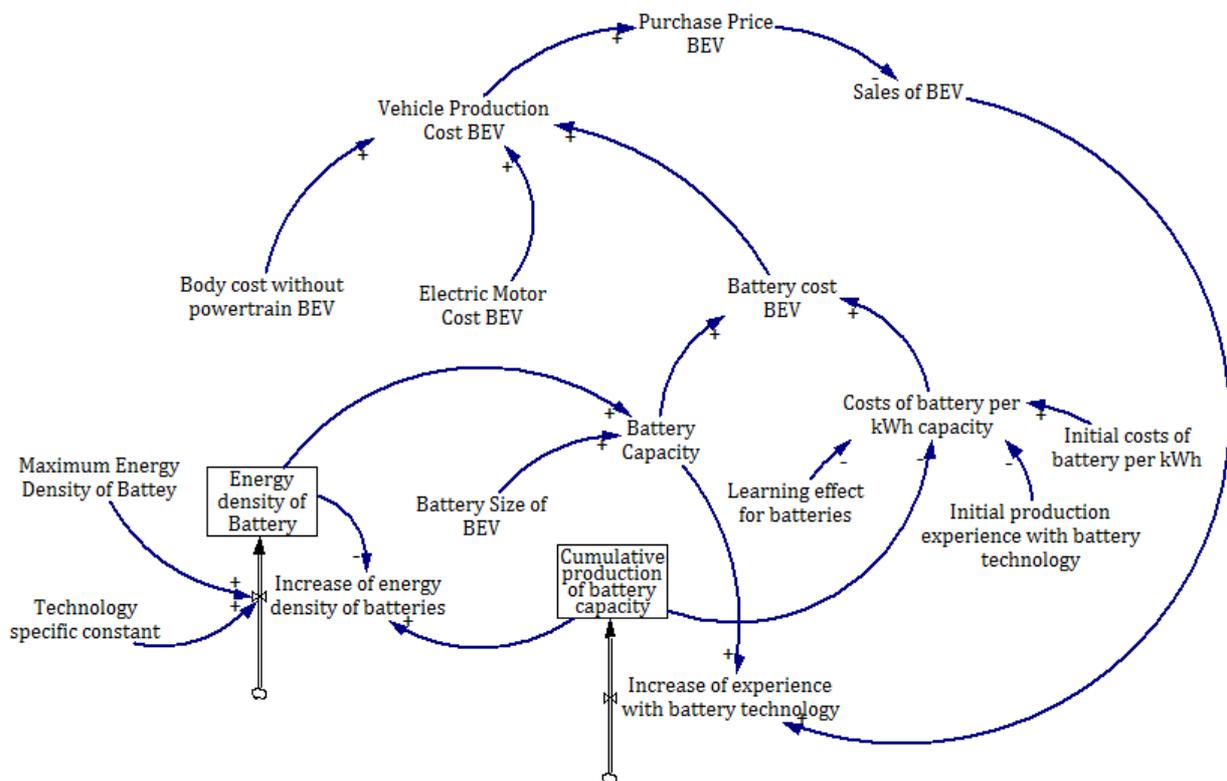


Figure 16 Calculation of battery electric truck production costs in System Dynamics

The Table 15 lists all fuel cell electric truck specific data needed for the equations.

Energy consumption [kWh/km]	$Q_i^{el}(t)$	1.9
Cost of fuel cell system per kW in the initial year [€/kW]	$c_{kW}^{FC}(t_0)$	244
Power of fuel cell system [kW]	$Pow_{FCEV}^{FC}(t)$ :	110
Learning rate for fuel cell system [-]	$\lambda^{FC}$	0.2
Initial production experience for fuel cell system [kW]	$E_{kW}^{FC}(t_0)$	2,000
Cost of hydrogen tank per kg in the initial year [€/kW]	$c_{kg}^{H_2}(t_0)$	483
Mass of hydrogen in the tank [kg]	$m_{H_2}$	7.6

Table 15 Technical values for the fuel cell electric truck<sup>562</sup>

### 4.2.3 INFRASTRUCTURE PERSPECTIVE

In this section, the implementation of the public battery charging points (BCPs) and hydrogen refuelling stations (HRSs) development in System Dynamics will be explained. It should first be noted that especially forecasting the number of required rapid charging points is difficult as the diffusion rates of battery electric trucks are uncertain and still little is known about the usage behavior of battery electric trucks owners.<sup>563</sup> The public battery charging point and hydrogen refuelling stations development is implemented as follows: the higher the number of battery electric trucks and fuel cell electric trucks in the vehicle stock, the higher is the target number of public battery charging points and hydrogen refuelling stations that are needed to charge and refuel these trucks.<sup>564</sup> The number of public battery charging points and hydrogen refuelling stations approaches these target numbers with a delay factor which represents the construction duration of public battery charging points and

<sup>562</sup> Daimler AG

<sup>563</sup> Naberezhnykh et al. (2012), p. 34

<sup>564</sup> Kieckhäfer, K. (2013), p. 92

hydrogen refuelling stations.<sup>565</sup> The construction duration for battery charging points is assumed to be one year, whereas the construction duration of hydrogen refuelling stations is two years.<sup>566</sup>

$$\frac{d}{dt} S_i(t) = \frac{S_i^{\text{tar}}(t) - S_i(t)}{T^{\text{inst}}} \quad ( 84 )$$

$\frac{d}{dt} S_{\text{BCP}}(t)$ : Public battery charging point construction [Charging point/Year]

$\frac{d}{dt} S_{\text{HRS}}(t)$ : Hydrogen refuelling station construction [Station/year]

$S_{\text{BCP}}(t)$ : Number of public battery charging points in year t [Charging point]

$S_{\text{HRS}}(t)$ : Number of hydrogen refuelling stations in year t [Station]

$S_{\text{BCP}}^{\text{tar}}(t)$ : Target number of public battery charging points [Charging point]

$S_{\text{HRS}}^{\text{tar}}(t)$ : Target number of hydrogen refuelling stations [Station]

$T_{\text{BCP}}^{\text{inst}}$ : Public battery charging point construction duration [Year]

$T_{\text{HRS}}^{\text{inst}}$ : Hydrogen refuelling station construction duration [Year]

The following example describes how the infrastructure development works: it is assumed that the present stock of fuel cell electric trucks requires a target number 20 hydrogen refuelling stations, 10 hydrogen refuelling stations are existent and the hydrogen refuelling station construction duration is 2 years. According to the equation ( 84 ) above, five hydrogen refuelling stations would be built  $((20-10)/2)$  in the respective year. The government supports the construction of a minimum number of public battery charging points and hydrogen refuelling stations to start and accelerate the uptake of green technologies in the freight market.<sup>567</sup> The British government announced the Ultra-Low Emission Strategy, which includes funding for hydrogen refuelling stations.<sup>568</sup> In addition to that, a new law has been announced in the Queen's Speech that would require gas stations and fuel suppliers to install chargers

<sup>565</sup> Kieckhäfer, K. (2013), p. 92

<sup>566</sup> Teter et al. (2017), p. 100

<sup>567</sup> Thies et al. (2016), p. 12

<sup>568</sup> Cluzel, C. and Hope-Morley, A. (2015), p. 30

for electric vehicles.<sup>569</sup> Shell opened its first hydrogen refuelling station in 2017.<sup>570</sup> There were five large-scale hydrogen refuelling stations in operation in UK cities by the end of 2015 and five additional stations were under construction.<sup>571</sup> To serve both passenger and commercial vehicle customers, the stations need to be equipped with dual-pressure dispensers (700/350bar), as commercial vehicles are generally refuelled at 350 bar instead of 700 bar.<sup>572</sup> A minimum number of hydrogen charging points and refuelling stations will help to overcome the chicken-egg-problem for truck manufacturers, fuel suppliers, and truck customers.<sup>573</sup> Because, as long as the utilization of refuelling stations is expected to be low, private investors will not be willing to invest in hydrogen refuelling stations. On the other hand, customers will not buy trucks that cannot be fuelled and truck manufacturers will not offer fuel cell electric trucks as long as there is no existing customer demand. Therefore, a minimum number of hydrogen refuelling stations are needed to start the market diffusion of electric trucks.<sup>574</sup> If charging/refuelling demand exceeds the supply, additional charging/refuelling stations are built. The charging/refuelling demand, which is equal to the target number of public battery charging points and hydrogen refueling stations, is calculated as vehicle stock divided by the number of trucks that can be served at a public battery charging point or a hydrogen refuelling station.<sup>575</sup>

$$S_i^{\text{tar}}(t) = \max\left(S_i^{\text{min}}(t), \frac{F_i(t)}{G_i^{\text{av}}(t)}\right) \quad (85)$$

- $S_{\text{BCP}}^{\text{min}}(t)$ : Minimum number of BCPs enforced by the government [Charging point]  
 $S_{\text{HRS}}^{\text{min}}(t)$ : Minimum number of HRSs enforced by the government [Station]  
 $F_i(t)$ : Stock of truck type i [Truck]  
 $G_{\text{BCP}}^{\text{av}}(t)$ : Number of BEVs that can be charged at a BCP [Truck/Charging point]

<sup>569</sup> LoCITY (2017b), URL see Bibliography

<sup>570</sup> Markillie, R. (2017), URL see Bibliography

<sup>571</sup> Cluzel, C. and Hope-Morley, A. (2015b), p. 16

<sup>572</sup> Ibid., p. 42

<sup>573</sup> Klemick et.al. (2015), p. 161

<sup>574</sup> Cluzel, C. and Hope-Morley, A. (2015b), p. 41

<sup>575</sup> Kieckhäfer, K. (2013), p. 92

$G_{FCEV}^{av}(t)$ : Number of FCEVs that can be refuelled at a HRS [Truck/Station]

The number of battery electric trucks and fuel cell electric trucks that can be charged or refuelled at a battery charging point/hydrogen refuelling station is dependent on the charging/refuelling capacity of the battery charging point and the hydrogen refuelling station and the time between two charging/refuelling processes.<sup>576</sup>

$$G_k^{av}(t) = \frac{G_k^{cap}}{T_{cyc, i}(t)}, k \in \{BCP, HRS\} \quad ( 86 )$$

$G_{BCP}^{cap}$ : Capacity of battery charging point [Truck/Charging point\*day]

$G_{BCP}^{cap}$ : Capacity of hydrogen refuelling station [Truck/Station\*day]

$T_{cyc, i}(t)$ : Cycle time between two charging/refuelling operations [day]

The cycle time between two charging/refuelling processes is determined by the driving range and the daily mileage of the truck.<sup>577</sup>

$$T_{cyc, i}(t) = \frac{D_{e, i}(t)}{L} \quad ( 87 )$$

$T_{cyc, i}(t)$ : Cycle time between two charging/refuelling operations [day]

$D_{e, i}$ : Electric driving range of electric truck type i [km]

L: Daily mileage of 133 km [km]

A battery charging point can charge 32 trucks per day (16 hours work-day) if a charging time of 30 minutes is assumed. A hydrogen refuelling station can refuel 96 trucks per day (16 hours work-day) if a refuelling time of 10 minutes is assumed.

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<sup>576</sup> Kieckhäfer, K. (2013), p. 92

<sup>577</sup> Ibid.

Infrastructure availability is implemented as a lookup function of the actual and desired number of battery charging points/hydrogen refuelling stations and ranges in the interval between 0 and 100 percent. As the refuelling station coverage for diesel trucks is already on the desired level, the infrastructure availability for diesel trucks is set at 100 percent. Plug-in hybrid electric trucks also have an infrastructure availability of 100 percent, as they can switch to the diesel engine when there is no battery charging points or the battery is already depleted.<sup>578</sup>

$$IA_i(t) = f(S_i, S_i^{des}) \quad ( 88 )$$

$IA_i(t)$ : Infrastructure availability in percent [-]

$S_i^{des}$ : Desired number of BCPs/HRSs for full coverage [Station]

The desired number of rapid battery charging points is set as 1,000, and the desired number of hydrogen refuelling stations is set as 200. It is assumed that these numbers represent a full coverage with battery charging points and hydrogen refuelling stations.

The following Table 16 lists all battery charging point and hydrogen refuelling station specific data needed for the equations in this chapter.

Construction duration of battery charging point [year]	$T_{BCP}^{inst}$	1
Construction duration of hydrogen refuelling station [year]	$T_{HRS}^{inst}$	2
The capacity of hydrogen refuelling station [trucks/HRS*day]	$G_{HRS}^{cap}$	96
Capacity of battery charging point [trucks/BCP*day]	$G_{BCP}^{cap}$	32
Refuelling stations coverage for diesel trucks [-]	$IA_{ICEV}(t)$ :	100
Refuelling stations coverage for plug-in hybrid electric truck [-]	$IA_{PHEV}(t)$ :	100
The desired number of battery charging points for full coverage [stations]	$S_{BCP}^{des}$ :	1,000

<sup>578</sup> Thies et al. (2016), p. 12

The desired number of hydrogen refuelling stations for full coverage [stations]	$S_{HRS}^{des}$ :	200
Minimum number of battery charging points [stations]	$S_{BCP}^{min}(t)$	150
Minimum number of hydrogen refuelling stations [stations]	$S_{HRS}^{min}(t)$	10

Table 16 Parameter values for infrastructure development

Service stations only gradually acquire knowledge and equipment to maintain and repair electric trucks in parallel to the slow diffusion of electric trucks in the market. Therefore, the increase in stations with skilled labor and appropriate maintenance and repair equipment is delayed by the adaptation factor. The target coverage with service stations is 100 percent, and the delay factor for service station increase is four years.

$$\frac{d}{dt} SA_{EV}(t) = \frac{SA_{EV}^{tar}(t) - SA_{EV}(t)}{\tau_{adapt}}, EV \in \{PHEV, BEV, FCEV\} \quad (89)$$

$\frac{d}{dt} SA_{EV}(t)$ : Percentage increase of service stations for EVs per year [-]

$SA_{EV}(t)$ : Percentage of service stations for EVs [-]

$SA_{EV}^{tar}(t)$ : Target percentage of service stations for EVs [-]

$\tau_{adapt}$ : Delay factor for service station increase [Year]

The following Figure 17 shows the implementation of the calculation of public infrastructure development for battery electric trucks in System Dynamics.

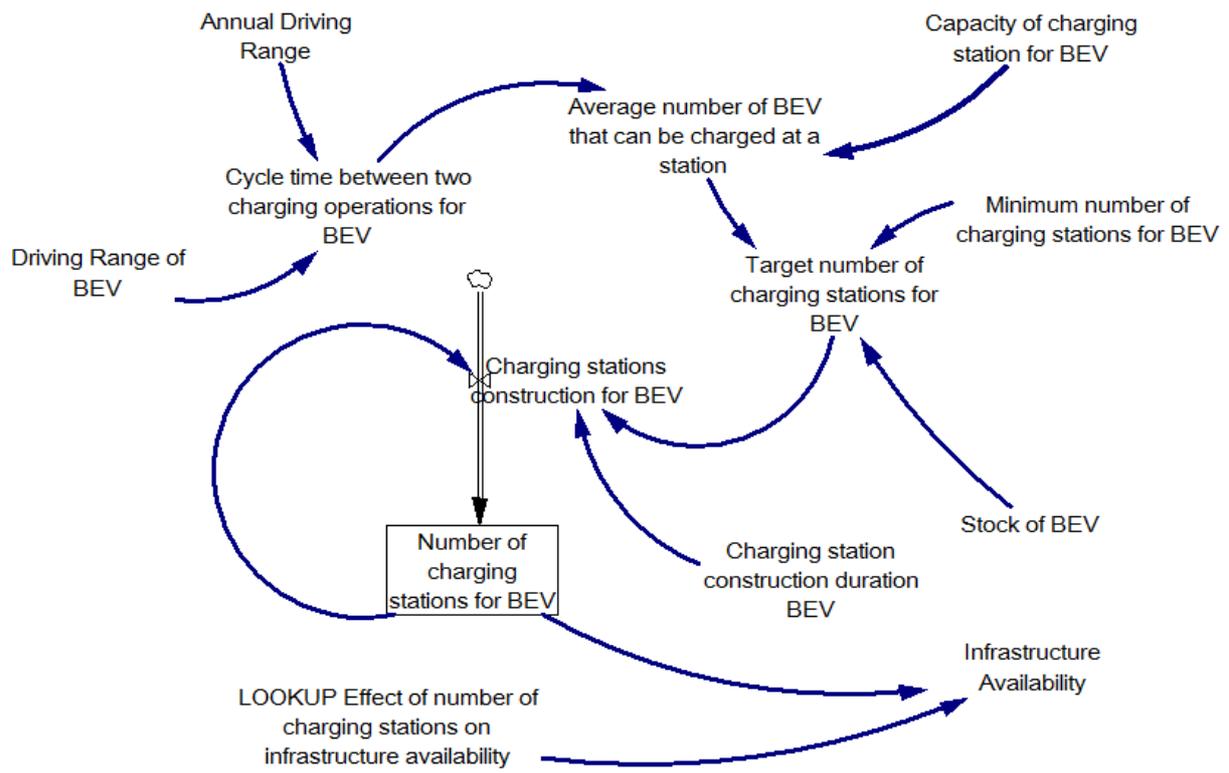


Figure 17 Calculation of the public infrastructure development for the battery electric truck in System Dynamics

#### 4.2.4 ENVIRONMENT PERSPECTIVE

A distinction has to be made between direct greenhouse gas emissions and indirect greenhouse gas emissions. Direct emissions, which are also called tailpipe emissions or Tank-to-Wheel emissions (TTW), are produced during the combustion of fuel. The creation of indirect emissions occurs in the upstream production, transport, and distribution of the energy carrier. These emissions are also known as Well-to-Tank emissions (WTT). In total, Well-to-Tank emissions (WTT) and Tank-to-Wheel emissions (TTW) add up to Well-to-Wheel emissions (WTW), which, however, do not include emissions that arise from the production and scrappage of vehicles (embedded emissions).<sup>579</sup>

<sup>579</sup> European Commission (2018b), URL see Bibliography

$$\text{CO}_{2,i}^{\text{WTW}} = \text{CO}_{2e}^{\text{WTT}} + \text{CO}_{2,i}^{\text{TTW}} \quad ( 90 )$$

$\text{CO}_{2,i}^{\text{WTW}}$ : Well-to-Wheel emissions [gCO<sub>2</sub>/km\*Truck]

$\text{CO}_{2e}^{\text{WTT}}$ : Well-to-Tank emissions [gCO<sub>2</sub>/km\*Truck]

$\text{CO}_{2,i}^{\text{TTW}}$ : Tank-to-Wheel emissions [gCO<sub>2</sub>/km\*Truck]

Battery electric trucks and fuel cell electric trucks do not produce any tailpipe emissions. The direct emissions of plug-in hybrid electric trucks and diesel trucks are a function of diesel fuel consumption and CO<sub>2</sub> intensity of diesel fuel. The Tank-to-Wheel CO<sub>2</sub> intensity of diesel fuel is 2,622 g CO<sub>2</sub> per litre.<sup>580</sup> With an average consumption of 20.9 litres of diesel fuel per 100 kilometres, the diesel truck emits 548 g CO<sub>2</sub> per km on average.

$$\text{CO}_{2,\text{Diesel}}^{\text{TTW}} = \xi_{\text{Diesel}}^{\text{CO}_2} * Q_{\text{Diesel}}^{\text{Diesel}}(t) \quad ( 91 )$$

$\text{CO}_{2,i}^{\text{TTW}}$ : CO<sub>2</sub> emissions output of a diesel truck [gCO<sub>2</sub>/km\*Truck]

$Q_{\text{Diesel}}^{\text{Diesel}}(t)$ : Average fuel consumption of a diesel truck [l/km\*Truck]

$\xi_{\text{Diesel}}^{\text{CO}_2}$ : CO<sub>2</sub> energy intensity of diesel fuel [g/l]

The actual fuel consumption of a plug-in hybrid electric truck is dependent on its duty cycle. It is assumed that the plug-in hybrid electric truck is operated in charge depleting mode until it switches to the diesel engine. Accordingly, the plug-in hybrid electric truck drives 29.35 km electrically and the rest of the duty cycle with the diesel engine in the initial year of the simulation period. Furthermore, it is assumed that the energy consumption in the charge depleting mode is equal to the energy consumption of a battery electric truck, even though the real energy consumption will be higher due to the weight of an additional drivetrain. The fuel consumption in the charge sustaining

<sup>580</sup> van der Slot et al. (2016), p. 88

mode is assumed to be equal to the fuel consumption of a diesel truck. For the calculation of the CO<sub>2</sub> emissions output of a plug-in hybrid electric truck, the equation ( 92 ) according to the norm ECE-R101 is applied.<sup>581</sup>

$$C(t) = \frac{D_{e, PHEV}(t) * C_1 - D_{AV} * C_2}{D_{e, PHEV}(t) + D_{AV}} = \frac{D_{AV} * C_2}{D_{e, PHEV}(t) + D_{AV}} \quad ( 92 )$$

- C (t): Combined fuel consumption according to ECE R101
- C<sub>1</sub> Fuel consumption in charge depleting mode [l/100km\*Truck]
- C<sub>2</sub>: Fuel consumption in charge sustaining mode [l/100km]
- D<sub>e, PHEV</sub>(t): Electric driving range of a plug-in hybrid electric truck [km]
- D<sub>AV</sub>: Subsequent journey of 25 km with diesel engine [km]

This equation ( 92 ) implies, the higher the electric driving range capability of a plug-in hybrid electric truck, the lower the CO<sub>2</sub> emissions automatically will be. This might be true for a constant daily driving range of 100 km, but if the plug-in hybrid electric truck is used for long distance trips, the CO<sub>2</sub> emissions output will be closer to the CO<sub>2</sub> emissions output of the diesel truck, as the combustion engine will be used most of the time. The CO<sub>2</sub> emissions of a plug-in hybrid electric truck are calculated by multiplying the combined fuel consumption with the CO<sub>2</sub> intensity of the diesel fuel.

$$CO_{2, PHEV}^{TTW}(t) = C(t) * \xi_{Diesel}^{CO_2} \quad ( 93 )$$

$$CO_{2, PHEV}^{TTW}(t_0) = \frac{25 * 20.9}{29.35 + 25} * 2622 \frac{g}{l} = 9.61 \frac{l}{100km * Truck} * 2622 \frac{g}{l} = 250.21 \frac{gCO_2}{km * Truck}$$

According to the equation ( 93 ), the CO<sub>2</sub> output of a plug-in hybrid electric truck, which can drive 29.35 km electrically, is 250.21 g per km.

<sup>581</sup> Harter et al. (2014), p. 16

The amount of greenhouse gas emissions produced upstream is dependent on the production pathway of diesel, electricity, and hydrogen. In case of diesel fuel, the production, refining and distribution results in emissions of 554.34 g CO<sub>2</sub>e per km in the UK.<sup>582</sup> This CO<sub>2</sub> equivalent (CO<sub>2</sub>e) number comprises all greenhouse gases, which are carbon dioxide (CO<sub>2</sub>), “methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF<sub>6</sub>).”<sup>583</sup> The Well-to-Tank emissions of electricity in the UK were 412.05 g CO<sub>2</sub>e per km in 2016.<sup>584</sup> This figure fluctuates depending on factors like the share of renewably produced electricity. The greenhouse gas intensity of hydrogen is also dependent on the production pathway. It is expected that hydrogen will be produced with methane or via electrolysis until 2030.<sup>585</sup> At the beginning of the simulation period, it is assumed that hydrogen is mainly produced via methane reformation. Towards the end of the next decade, the hydrogen gets greener, as renewable energy sources like wind will be used increasingly for hydrogen production. The Well-to-Tank (WTT) greenhouse gas intensity of hydrogen with natural gas as an energy source is 104.3 g CO<sub>2</sub>e/MJ and the Well-to-Tank greenhouse gas intensity of hydrogen produced with electricity generated from wind is 13.0 g CO<sub>2</sub>e/MJ.<sup>586</sup> For reasons of simplification, it is assumed that the Well-to-Tank greenhouse gas intensity of hydrogen is 100 g CO<sub>2</sub>e/MJ in the initial year. MJ is converted to kWh with a conversion factor of 0.27778 (1 kWh = 3.6 MJ).<sup>587</sup> This leads to a Well-to-Tank greenhouse gas intensity of 360 g CO<sub>2</sub>e/kWh. It is necessary to multiply this value with the fuel consumption of a fuel cell electric truck per km to calculate the greenhouse gas intensity per km. With fuel consumption of 1.9 kWh per km, this results in a Well-to-Tank greenhouse gas intensity of 684 g CO<sub>2</sub>e/km at the beginning of the simulation period. Thus, the Well-to-Wheel CO<sub>2</sub> emissions of a fuel cell electric truck are approximately 60 percent lower than of a diesel truck. The carbon intensity of hydrogen decreases from 100 g CO<sub>2</sub>e/MJ in the year 2017 to 60 g CO<sub>2</sub>e/MJ in 2030, 35 g CO<sub>2</sub>e/MJ in 2040 and 24 g CO<sub>2</sub>e/MJ in 2050.<sup>588</sup> The hydrogen-carbon intensity decreases linearly between those dates (see Figure 18). The

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<sup>582</sup> Department for Business, Energy & Industrial Strategy (2016a), WTT-fuels tab, URL see Bibliography

<sup>583</sup> Schmied, M. and Knörr, W. (2012), p. 16

<sup>584</sup> Department for Business, Energy & Industrial Strategy (2016a), UK electricity tab, URL see Bibliography

<sup>585</sup> Cluzel, C. and Hope-Morley, A. (2015b), p. 18

<sup>586</sup> van der Slot et al. (2016), p. 89

<sup>587</sup> Department for Business, Energy & Industrial Strategy (2016a), Conversions tab, URL see Bibliography

<sup>588</sup> den Boer et al. (2013), p. 116

reduction of carbon intensity of hydrogen production is implemented with the RAMP function in System Dynamics. The same approach is applied for electricity generation with a carbon intensity of electricity of 77 g CO<sub>2</sub>e/MJ in 2030, 46 g CO<sub>2</sub>e/MJ in 2040 and 27 g CO<sub>2</sub>e/MJ in 2050.<sup>589</sup> The Well-to-Tank CO<sub>2</sub> emissions of diesel fuel are kept constant throughout the simulation period, as the greenhouse gas emission from oil production can develop in two opposite directions. The greenhouse gas intensity of diesel fuel production could decrease due to the Fuel Quality Directive or increase due to the higher share of non-conventional oil in the production process.<sup>590</sup>

$$CO_{2, H2/el}^{WTT} = \frac{CarbInt^{H2/el}}{0.27778 \frac{kWh}{MJ}} Q_i^{el} \tag{ 94 }$$

CarbInt<sup>H2/el</sup>: Carbon intensity of hydrogen/electricity [g CO<sub>2</sub>e/MJ]

Q<sub>i</sub><sup>el</sup>: Energy consumption of truck type i [kWh/km]

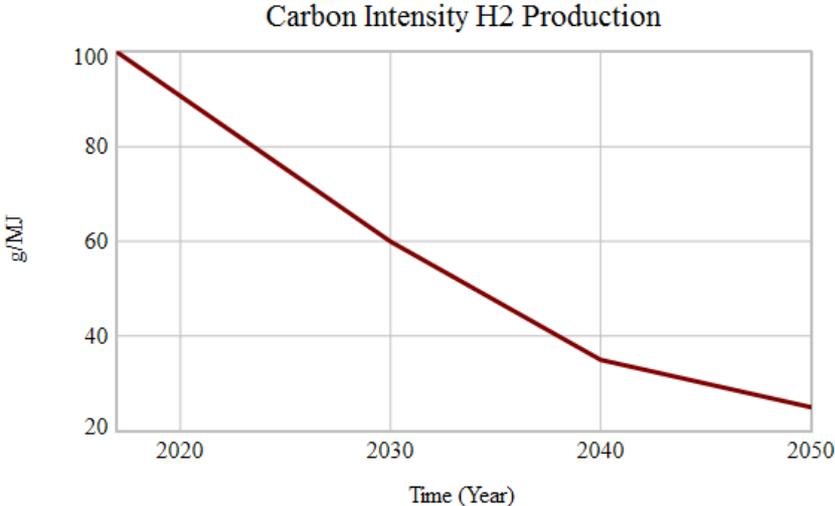


Figure 18 Carbon intensity of H<sub>2</sub> production

To calculate the CO<sub>2</sub>e savings from the diffusion of electric trucks, the following bottom-up approach is used.<sup>591</sup> GHG<sup>sav, cum</sup>(t) shows the amount of CO<sub>2</sub> savings that

<sup>589</sup> den Boer et al. (2013), p. 115  
<sup>590</sup> Ibid., p. 114  
<sup>591</sup> Kay, D. and Hill, N. (2012), p. 3

is achievable with the diffusion of electric trucks ( $\text{GHG}^{\text{TOTAL}}$ ) compared with a scenario in which only diesel trucks are offered ( $\text{GHG}^{\text{ALL ICEV}}$ ):

$$\text{GHG}^{\text{sav, cum}}(t) = \text{GHG}^{\text{ALL ICEV}}(t) - \text{GHG}^{\text{TOTAL}}(t) \quad (95)$$

$$\text{GHG}^{\text{ALL ICEV}}(t) = \sum_i \sum_t L * \text{CO}_{2,\text{ICEV}}^{\text{WTW}} * F_i(t) \quad (96)$$

$$\text{GHG}^{\text{TOTAL}}(t) = \sum_i \sum_t \text{AL} * \text{CO}_{2,i}^{\text{WTW}} * F_i(t) \quad (97)$$

- $\text{GHG}^{\text{sav, cum}}(t)$ :  $\text{CO}_2\text{e}$  emission difference [g]  
 $\text{GHG}^{\text{ALL ICEV}}(t)$ :  $\text{CO}_2\text{e}$  emissions when all trucks are diesel trucks [g]  
 $\text{GHG}^{\text{TOTAL}}(t)$ :  $\text{CO}_2\text{e}$  emissions of total fleet [g]  
AL: Annual mileage [km]  
 $F_i(t)$ : Actual stock of truck type i [Truck]

The average annual mileage AL of a distribution truck is assumed to be 40,000 km.<sup>592</sup>

The equation to calculate the relative  $\text{CO}_2\text{e}$  emissions savings is:<sup>593</sup>

$$\text{GHG}^{\text{sav, rel}}(t) = \frac{\text{GHG}^{\text{ALL ICEV}}(t) - \text{GHG}^{\text{TOTAL}}(t)}{\text{GHG}^{\text{ALL ICEV}}(t)} \quad (98)$$

<sup>592</sup> Dünnebeil et al. (2015), p. 103

<sup>593</sup> Turan, Ö. (2011), p. 47

$\text{GHG}^{\text{sav, rel}}(t)$ : Relative CO<sub>2</sub>e emissions reduction [-]

The following Figure 19 shows the implementation of the calculation of the relative CO<sub>2</sub> reduction potential in System Dynamics.

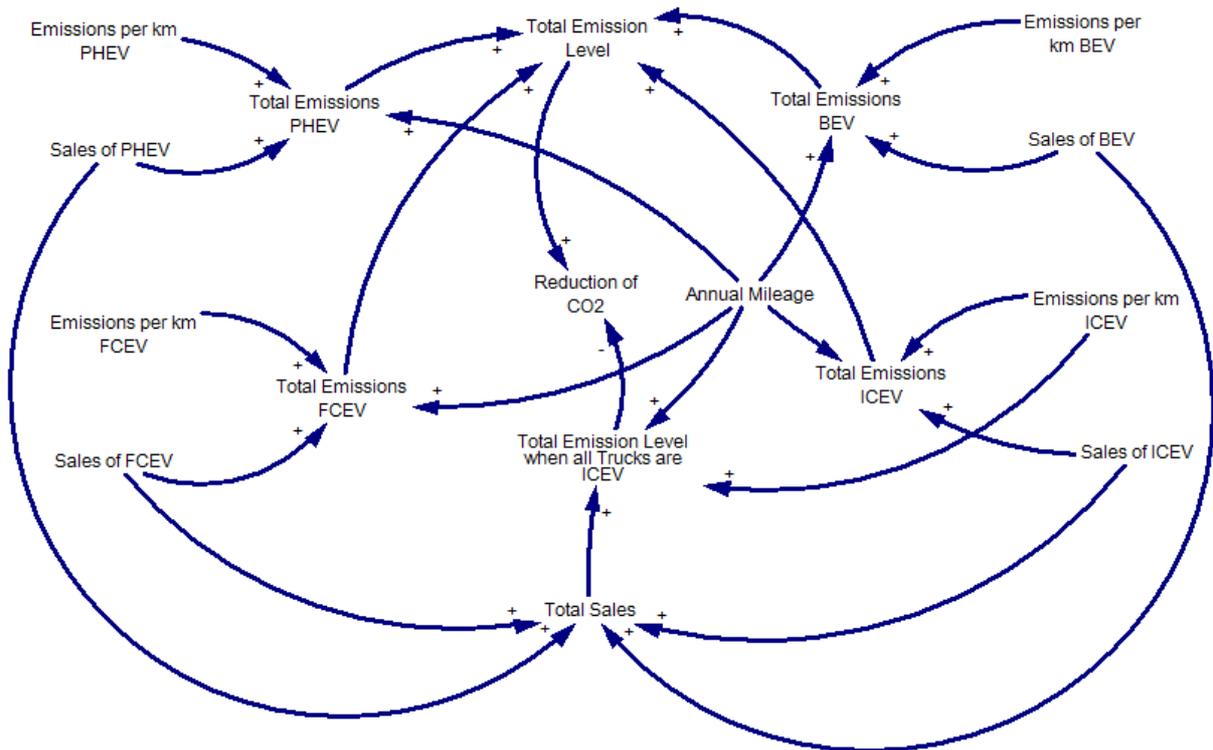


Figure 19 Calculation of CO<sub>2</sub> reduction potential in System Dynamics

The following Table 17 lists the data needed to calculate the Well-to-Wheel greenhouse gas emissions of trucks.

CO <sub>2</sub> energy intensity of Diesel [g/l]	$\xi_{\text{Diesel}}^{\text{CO}_2}$	2622
Well-to-Tank CO <sub>2</sub> e emissions of diesel [gCO <sub>2</sub> e/km*Truck]	$\text{CO}_{2e, \text{diesel}}^{\text{WTT}}$	554.34
Well-to-Tank CO <sub>2</sub> e emissions of electricity in the initial year [gCO <sub>2</sub> e/km*Truck]	$\text{CO}_{2e, \text{elec}}^{\text{WTT}}(t_0)$	412.05
Well-to-Tank CO <sub>2</sub> e emissions of hydrogen in the initial year [gCO <sub>2</sub> e/km*Truck]	$\text{CO}_{2e, \text{hydr}}^{\text{WTT}}(t_0)$	684
Tank-to-Wheel CO <sub>2</sub> emissions of a diesel truck in the initial year [gCO <sub>2</sub> /km*Truck]	$\text{CO}_{2, \text{ICEV}}^{\text{TTW}}(t_0)$	548

Tank-to-Wheel CO <sub>2</sub> emissions of a battery electric truck in the initial year [gCO <sub>2</sub> /km*Truck]	CO <sub>2, BEV</sub> <sup>TTW</sup> (t <sub>0</sub> )	0
Tank-to-Wheel CO <sub>2</sub> emissions of a fuel cell electric truck in the initial year [gCO <sub>2</sub> /km*Truck]	CO <sub>2, FCEV</sub> <sup>TTW</sup> (t <sub>0</sub> )	0
Tank-to-Wheel CO <sub>2</sub> emissions of a plug-in hybrid electric truck in the initial year [gCO <sub>2</sub> /km*Truck]	CO <sub>2, PHEV</sub> <sup>TTW</sup> (t <sub>0</sub> )	250.21

Table 17 Well-to-Tank and Tank-to-Wheel greenhouse gas emissions

#### 4.2.5 GOVERNMENT PERSPECTIVE

The model above does not offer the possibility to define policy measures and assess their effect on the uptake of zero-emission technologies in urban freight transport. However, policy design is one of the key aspects of System Dynamics modelling. This requires that the government, which is interested in influencing the market development of electric mobility in freight transport, is included as a stakeholder in the System Dynamics model. Thus, this chapter deals with the question what happens if an environment is assumed that is supportive to the uptake of electric trucks. Therefore, the model has been extended to include subsidies and the introduction of a CO<sub>2</sub> fleet target value for electric trucks by the government. In the following, the subsidy mechanism will be explained first.

Government subsidies for customers of electric vehicles are factored into the purchase price of electric trucks. In its quest to achieve the climate targets and back the demand for cleaner commercial vehicles, the British government has decided in October 2016 to make medium and heavy-duty trucks eligible for the Plug-in-Van grant scheme, which until then only encompassed light-duty vehicles.<sup>594</sup> Operators, were eligible to get grants up to £20,000 for an electric truck, but the grant scheme worth £4 million was restricted to 5,000 grants and expired in March 2018.<sup>595</sup> But comparable schemes are highly likely for the coming years. In Germany, the amount of subsidy on the purchase of an electric truck with a Gross Vehicle Weight Rating between 7.5 and 12 t is €12,000 and increases to €40,000 for an electric truck with a GVWR greater than 12

<sup>594</sup> Pink, H. (2016c), URL see Bibliography

<sup>595</sup> Ibid.

t.<sup>596</sup> The program worth €10 million will terminate end of 2020 and each grant is limited to €500,000 per company.<sup>597</sup>

Truck operators need to burden the costs of the depot charging infrastructure. Truck operators need to bear the cost of €10,000 for the depot-charger with a power of 22 kW for battery electric trucks and the costs of €1,050 for a wall-box with 3.7 kW power. This would mean that two battery electric trucks can be charged overnight in a two-shift operation. Given the cost of €10,000 per charger, which includes the installation costs, the charger cost per battery electric truck amounts to €5,000. The wall-box with 3.7 kW power can charge a plug-in hybrid electric truck in about seven hours. If the government gives grants for the charging infrastructure, the charger costs in the equation ( 99 ) are reduced by this amount.

$$\text{Price}_i(t) = -\text{Sub}_i(t) + \text{Price}_i^{\text{OEM}}(t) + \text{Ch}_i(t) \quad ( 99 )$$

Price<sub>i</sub>(t): Price of truck type i including the charger costs [€/Truck]

Sub<sub>i</sub>(t): Purchase subsidy for truck type i [€/Truck]

Ch<sub>i</sub>: Charger cost for truck type i [€/Truck]

Price<sub>i</sub><sup>OEM</sup>(t): Manufacturer's vehicle price of truck type i [€/Truck]

A high average operating profit margin is a sign of successful management, especially in a business like the trucking industry, which is characterized by a strong cyclical development. According to a report of Automotive World, a “margin of 5-7 percent is probably the lowest target range any truck producer is likely to set itself as a long-term cyclical average”.<sup>598</sup> The following Figure 20 shows the average operating margins of the major truck manufacturers between 2004 and 2013. Only one producer was able to achieve an average operating profit margin above ten percent. All the other producers remained below the seven percent mark. Therefore, an average profit

<sup>596</sup> Manthey, N. (2018), URL see Bibliography

<sup>597</sup> Ibid.

<sup>598</sup> Storey, J. (2014), p. 16

margin of ten percent can be seen as a target for truck manufacturers. Almost all truck manufacturers achieved a profit margin higher than three percent, which can be seen as the minimum profit margin.

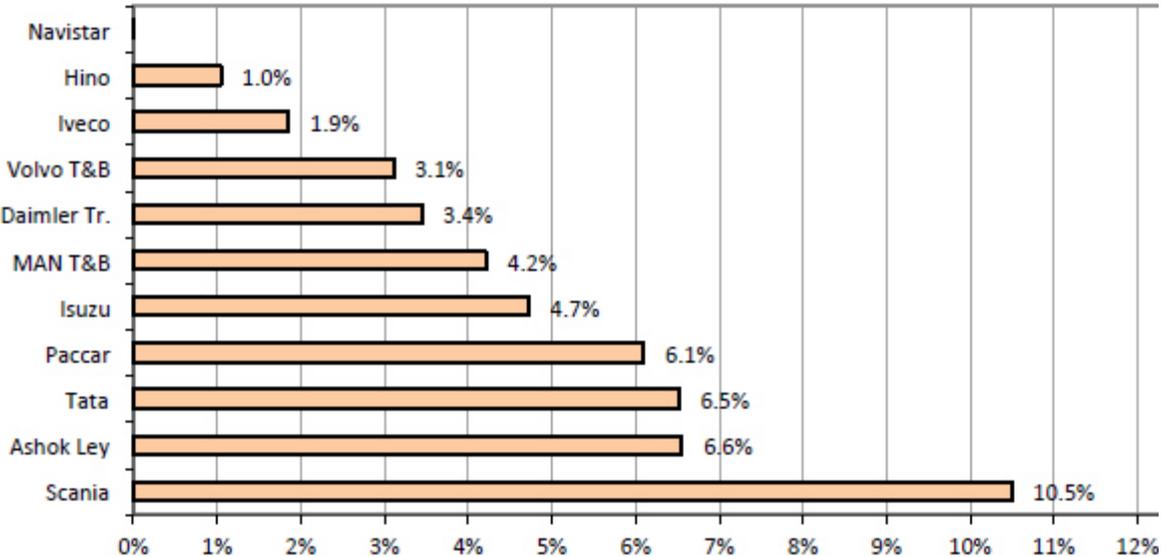


Figure 20 Operating margins of major truck manufacturers between 2004 and 2013<sup>599</sup>

In the following, it is explained how the operating profit margin is calculated. The gross operating profit of the truck industry is defined as revenue minus total costs.

$$\pi(t) = \text{rev}_{\text{tot}}(t) - c_{\text{tot}}(t) \tag{ 100 }$$

$\pi(t)$ : Gross operating profit of truck manufacturers [€]

$\text{rev}_{\text{tot}}(t)$ : Total revenue of truck manufacturers [€]

$c_{\text{tot}}(t)$ : Total costs of truck manufacturers [€]

The revenue generated by sales of trucks is calculated by multiplying the sales figures per truck type with the purchase price of the truck type.

<sup>599</sup> Storey, J. (2014), p. 15

$$\text{rev}_{\text{tot}}(t) = \sum_i r_i^{\text{sales}} * \text{Price}_i^{\text{OEM}}(t) \quad (101)$$

The total costs of the truck industry include the direct manufacturing costs and the CO<sub>2</sub> penalty payments. The amount of CO<sub>2</sub> penalty payment depends on the average CO<sub>2</sub> value of a manufacturer's new sales fleet. The higher the share of zero-emission vehicles, the lower is the CO<sub>2</sub> penalty payment.

$$c_{\text{tot}}(t) = \sum_i (r_i^{\text{sales}} * C_i^{\text{OEM}}(t)) + c_{\text{CO}_2}^{\text{pen}} \quad (102)$$

$c_{\text{tot}}(t)$ : Total costs of truck manufacturers [€]

$r_i^{\text{sales}}(t)$ : Sales rate of truck type i [Truck/Year]

$C_i^{\text{OEM}}(t)$ : Vehicle production costs [€/Truck]

$c_{\text{CO}_2}^{\text{pen}}$ : CO<sub>2</sub> penalty payment [€]

The operating profit margin or return on sales is a key figure to measure the operational efficiency of a truck manufacturer. This figure allows comparing the profitability of different truck manufacturers regardless of their different company sizes and structures. The operating profit margin could be used to define truck pricing strategies for the next selling period. However, this would increase model complexity without providing an important added explanatory value.

$$\text{ROS}(t) = \left( \frac{\text{rev}_{\text{tot}}(t) - c_{\text{tot}}(t)}{c_{\text{tot}}(t)} \right) \quad (103)$$

$\text{ROS}(t)$ : Operating profit margin or return on sales [€]

$\text{rev}_{\text{tot}}(t)$ : Total revenue of truck manufacturers [€]

$c_{\text{tot}}(t)$ : Total costs of truck manufacturers [€]

The following Figure 21 shows the implementation of the calculation of the gross profit margin in System Dynamics.

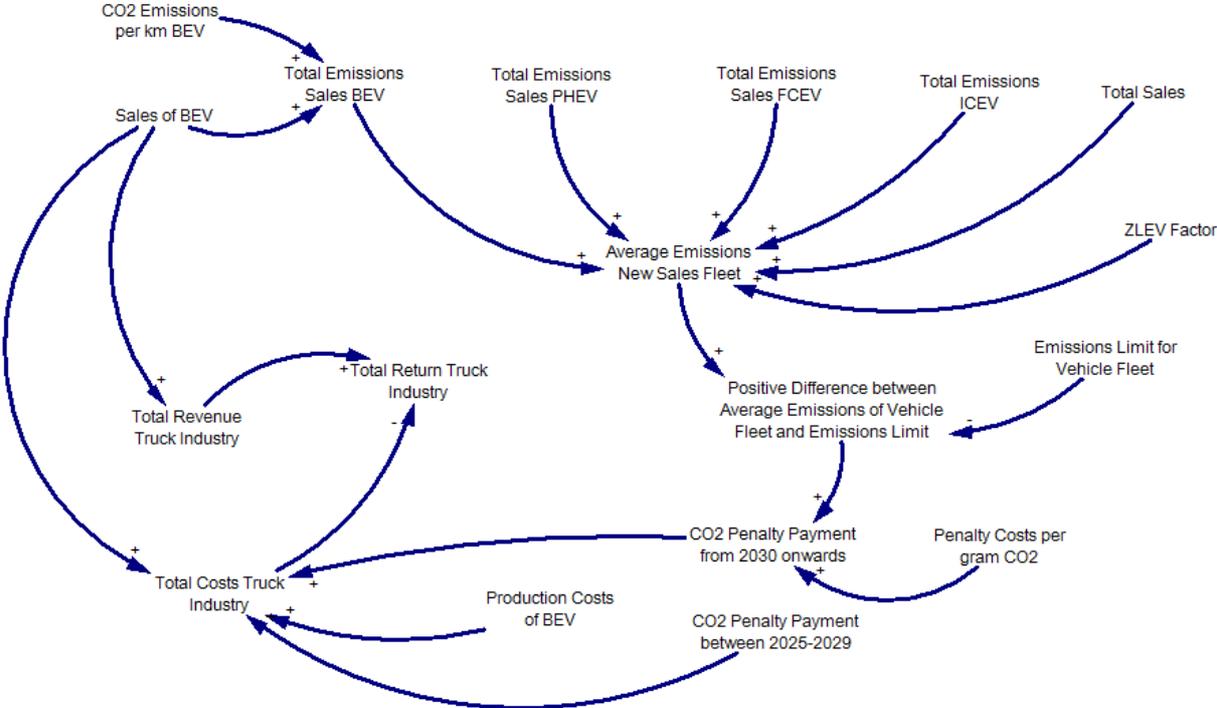


Figure 21 Calculation of the gross profit margin in System Dynamics

The truck manufacturer can increase the marketing efforts to boost sales of electric trucks. Marketing activities are important to limit greenhouse gas penalty payments. The marketing efforts return to their old level once the CO<sub>2</sub> target is reached.

$$\frac{d}{dt} \alpha_{EV}(t) = \alpha_{EV}(t) * \text{MAX} \left( \frac{CO_2^{av}(t)}{CO_2^{lim}(t)}, 1 \right) \tag{104}$$

CO<sub>2</sub><sup>av</sup>(t): Average specific emissions [gCO<sub>2</sub>/km\*Truck]

CO<sub>2</sub><sup>lim</sup>(t): Specific emission target [gCO<sub>2</sub>/km\*Truck]

α<sub>EV</sub>: Marketing efforts targeted towards electric trucks [-]

Truck manufacturers are fined for every gram with which they exceed their CO<sub>2</sub> fleet target value. A penalty cost of €570 for each gram CO<sub>2</sub> per km exceeding the CO<sub>2</sub> emissions limit is applied, instead of a stepwise increase in penalty payments with each additional gram of exceedance in the first years of the CO<sub>2</sub> regulation. For reasons of simplicity, the metric g CO<sub>2</sub> per km is used instead of g CO<sub>2</sub> per tkm, as the fuel consumption values are given in litres per km. The reference CO<sub>2</sub> emissions value for the year 2019 is the CO<sub>2</sub> emissions output of a diesel truck in 2019. According to the EU proposal, the average specific CO<sub>2</sub> emissions need to be reduced by 15% (rf(2025)) until 2025, which corresponds to a CO<sub>2</sub> emissions limit of 466 g per km for the whole industry given a CO<sub>2</sub> emissions reference value of 548 g CO<sub>2</sub> per km, as the model does not distinguish between truck manufacturers and treats them as one entity (see Table 17).<sup>600</sup> Accordingly, the CO<sub>2</sub> emissions limit for 2030 would be 384 g CO<sub>2</sub> per km. These are rounded up limit values.

$$CO_2^{lim}(2025)=CO_{2,ICEV}^{TTW}(2019)*(1-rf(2025)) \quad ( 105 )$$

$$CO_2^{lim}(2030)=CO_{2,ICEV}^{TTW}(2019)*(1-rf(2030)) \quad ( 106 )$$

CO<sub>2</sub><sup>lim</sup>: Specific CO<sub>2</sub> emissions target [gCO<sub>2</sub>/km\*Truck]

rf: CO<sub>2</sub> reduction target [-]

CO<sub>2,ICEV</sub><sup>TTW</sup>(2019): Reference CO<sub>2</sub> emission value in 2019 [gCO<sub>2</sub>/km\*Truck]

As the dissertation treats truck manufacturers as one entity and does not distinguish between different truck subgroups, the calculation of the average specific CO<sub>2</sub> emissions of a manufacturer does not include the manufacturer's share of trucks in a sub-group, the average specific CO<sub>2</sub> emissions of all new trucks in a sub-group, and a

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<sup>600</sup> European Commission (2018a), URL see Bibliography

mileage and payload weighting factor of a sub-group.<sup>601</sup> These factors, however, will be taken into account for the determination of the average specific CO<sub>2</sub> emissions of a manufacturer.

For reasons of simplicity, the average specific CO<sub>2</sub> emissions of the new sales fleet are calculated as follows:

$$CO_2^{av}(t) = ZLEV * \frac{\sum_i CO_{2,i}^{TTW} * r_i^{sales}(t)}{\sum_i r_i^{sales}(t)} \quad (107)$$

CO<sub>2</sub><sup>av</sup>(t): Average specific emissions [gCO<sub>2</sub>/km\*Truck]

CO<sub>2,i</sub><sup>TTW</sup>: Tank-to-Wheel CO<sub>2</sub> emissions of truck type i [gCO<sub>2</sub>/km\*Truck]

r<sub>i</sub><sup>sales</sup>(t): Sales rate of truck type i [Truck/Year]

ZLEV: Zero- and low-emission factor [-]

The zero- and low-emission factor helps manufacturers in achieving the CO<sub>2</sub> emission target by allowing zero-emission vehicles to be counted as two vehicles and low emission vehicles as up to two vehicles depending on the specific CO<sub>2</sub> emissions.<sup>602</sup> However, there is the restriction that zero- and low- emission vehicles cannot reduce the average specific CO<sub>2</sub> emissions of a manufacturer more than 3%.<sup>603</sup> That is why the ZLEV factor cannot have values smaller than 0.97. The ZLEV factor is calculated as follows:

$$ZLEV(t) = \text{MAX} \left( \frac{\sum_i r_i^{sales}(t)}{r_{DIESEL}^{sales}(t) + \left( 1 + \left( 1 - \frac{CO_{2,PHEV}^{TTW}}{350} \right) \right) * r_{PHEV}^{sales}(t) + 2 * r_{BEV}^{sales}(t) + 2 * r_{FCEV}^{sales}(t)}, 0.97 \right) \quad (108)$$

<sup>601</sup> European Commission (2018a), URL see Bibliography

<sup>602</sup> Ibid.

<sup>603</sup> Ibid.

ZLEV(t): Zero- and low-emission factor [-]

$r_i^{\text{sales}}(t)$ : Sales rate of truck type i [Truck/Year]

$\text{CO}_{2,\text{PHEV}}^{\text{TTW}}$ : Tank-to-Wheel CO<sub>2</sub> emissions of a plug-in hybrid electric truck [gCO<sub>2</sub>/km\*Truck]

Manufacturers are allowed to bank and borrow CO<sub>2</sub> emission credits. It is necessary to define the CO<sub>2</sub> emissions reduction trajectory from 2019 to 2029 for the calculation of emission credits.<sup>604</sup> The emission trajectory is defined as follows:

$$\text{ET}(t) = \text{CO}_{2,\text{ICEV}}^{\text{TTW}}(2019) * \text{RETY}(t) \quad ( 109 )$$

ET(t): Emission trajectory [gCO<sub>2</sub>/km\*Truck]

$\text{CO}_{2,\text{ICEV}}^{\text{TTW}}(2019)$ : Reference CO<sub>2</sub> emission value [gCO<sub>2</sub>/km\*Truck]

RETY(t): Emission trajectory reduction factor [-]

For the calendar years t from 2019 to 2025, the emission trajectory foresees a linear reduction of the reference CO<sub>2</sub> emission value, until the CO<sub>2</sub> emissions limit in 2025 is achieved.<sup>605</sup>

$$\text{RETY}(t) = (1 - \text{rf}(2025)) + \text{rf}(2025) * \frac{(2025-t)}{6} \quad ( 110 )$$

RETY(t): Emission trajectory reduction factor [-]

rf(2025): CO<sub>2</sub> reduction target of 15% for 2025 [-]

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<sup>604</sup> European Commission (2018a), URL see Bibliography

<sup>605</sup> Ibid.

For the calendar years t from 2026 to 2030, RETY is defined correspondingly as:<sup>606</sup>

$$\text{RETY}(t) = (1 - \text{rf}(2030)) + (\text{rf}(2030) - \text{rf}(2025)) * \frac{(2030-t)}{5} \quad (111)$$

- RETY(t): Emission trajectory reduction factor [-]  
 rf(2030): CO<sub>2</sub> reduction target of 30% for 2030 [-]  
 rf(2025): CO<sub>2</sub> reduction target of 15% for 2025 [-]

The collection of credits between 2019 and 2029, which is termed banking, can be seen as a reward mechanism for manufacturers that invest in fuel-saving technologies before the CO<sub>2</sub> emissions limit is introduced.<sup>607</sup> Emission credits Cr<sub>CO<sub>2</sub></sub>(t) are generated if the average specific CO<sub>2</sub> emissions value in a calendar year is smaller than the CO<sub>2</sub> value defined by the emission trajectory for that year.<sup>608</sup>

$$\text{Cr}_{\text{CO}_2}(t) = \left( \text{ET}(t) - \text{CO}_2^{\text{av}}(t) \right) * r_{\text{total}}^{\text{sales}}(t) \quad (112)$$

- Cr<sub>CO<sub>2</sub></sub>(t): CO<sub>2</sub> emission credits [gCO<sub>2</sub>/km]  
 ET(t): Emission trajectory [gCO<sub>2</sub>/km\*Truck]  
 CO<sub>2</sub><sup>av</sup>(t): Average specific emissions [gCO<sub>2</sub>/km\*Truck]  
 r<sub>total</sub><sup>sales</sup>(t): Total sales rate of trucks [Truck/Year]

The credits lose their validity in 2030 and thus must be used no later than 2029.<sup>609</sup> If the average specific CO<sub>2</sub> emissions of the manufacturer are higher than the emission

<sup>606</sup> European Commission (2018a), URL see Bibliography

<sup>607</sup> Ibid.

<sup>608</sup> Ibid.

<sup>609</sup> Ibid.

target of that calendar year starting with 2025, the manufacturer is allowed to borrow CO<sub>2</sub> credits to avoid CO<sub>2</sub> penalties and in the hope to be able to settle the emission debts in the following years:<sup>610</sup>

$$De_{CO_2}(t) = (CO_2^{av}(t) - ET(t)) * r_{total}^{sales}(t) \quad (113)$$

$De_{CO_2}(t)$ : CO<sub>2</sub> emission debts [gCO<sub>2</sub>/km]

$CO_2^{av}(t)$ : Average specific emissions [gCO<sub>2</sub>/km\*Truck]

$ET(t)$ : Emission trajectory [gCO<sub>2</sub>/km\*Truck]

$r_{total}^{sales}(t)$ : Total sales rate of trucks [Truck/Year]

Borrowing cannot exceed 5 percent of the manufacturers' specific emission target in 2025 and the latest possible date to clear an emission debt is 2029:<sup>611</sup>

$$De_{CO_2}^{lim}(t) = CO_2^{lim}(2025) * 0.05 * r_{total}^{sales}(2025) \quad (114)$$

$De_{CO_2}^{lim}(t)$ : Emission debt limit [gCO<sub>2</sub>/km]

$CO_2^{lim}(2025)$ : Specific CO<sub>2</sub> emissions target for 2025 [gCO<sub>2</sub>/km\*Truck]

$r_{total}^{sales}(2025)$ : Total sales rate of trucks in 2025 [Truck/Year]

CO<sub>2</sub> credits earned between 2019 and 2024 can be deducted from the manufacturer's CO<sub>2</sub> emissions target for 2025 only.<sup>612</sup> The excess emissions for the year 2025 are thus calculated as follows:

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<sup>610</sup> European Commission (2018a), URL see Bibliography

<sup>611</sup> Ibid.

<sup>612</sup> Ibid.

$$\text{Exe}_{\text{CO}_2}(2025) = \text{De}_{\text{CO}_2}(2025) - \sum_{t=2019}^{2025} \text{Cr}_{\text{CO}_2}(t) - \text{De}_{\text{CO}_2}^{\text{lim}} \quad (115)$$

$\text{Exe}_{\text{CO}_2}(2025)$ : Excess CO2 emissions in 2025 [gCO<sub>2</sub>/km]

$\text{De}_{\text{CO}_2}(2025)$ : CO<sub>2</sub> emission debts in 2025 [gCO<sub>2</sub>/km]

$\text{Cr}_{\text{CO}_2}(t)$ : CO<sub>2</sub> emission credits [gCO<sub>2</sub>/km]

$\text{De}_{\text{CO}_2}^{\text{lim}}(t)$ : Emission debt limit [gCO<sub>2</sub>/km]

Aging chains are used to model the stock- and flow structure of the CO<sub>2</sub> emission credits generation between 2026 and 2028, as they “allow you to model changes in the age structure of any stock.”<sup>613</sup> The CO<sub>2</sub> emission credits and debts respectively are collected in so-called cohorts, which altogether represent the total stock in an aging chain. There are in total four cohorts, as the emission credit debt has to be closed after four years in 2029 and ZEV credits lose their validity respectively.<sup>614</sup> Each cohort is characterized by an inflow and an outflow of CO<sub>2</sub> emission credits, and the credits move between the cohorts with the transition rate  $T(a, a+1)$ , which is one year in this case.<sup>615</sup>

For the years from 2026 to 2028, the excess emissions are calculated as:<sup>616</sup>

$$\text{Exe}_{\text{CO}_2}(t) = \text{De}_{\text{CO}_2}(t) - \text{Cr}_{\text{CO}_2}(t) + \sum_{t=2025}^{t-1} \text{Exe}_{\text{CO}_2}(t-1) \quad (116)$$

$\text{Exe}_{\text{CO}_2}(t)$ : Excess CO2 emissions in year t [gCO<sub>2</sub>/km]

$\text{Exe}_{\text{CO}_2}(t-1)$ : Transferred excess emissions (if positive) [gCO<sub>2</sub>/km]

$\text{De}_{\text{CO}_2}(t)$ : CO<sub>2</sub> emission debts [gCO<sub>2</sub>/km]

<sup>613</sup> Sterman, J. D. (2000), p. 470

<sup>614</sup> Ibid.

<sup>615</sup> Ibid., p. 470 f.

<sup>616</sup> European Commission (2018a), URL see Bibliography

$Cr_{CO_2}(t)$ :  $CO_2$  emission credits [gCO<sub>2</sub>/km]

The emission debt has to be cleared until 2029. For this reason, the emission debt limit is not applied in the year 2029. This is achieved by adding the emission debt limit at the end of the period of validity.

$$Exe_{CO_2}(2029) = De_{CO_2}(2029) - Cr_{CO_2}(2029) + \sum_{t=2025}^{t-1} Exe_{CO_2}(t-1) + De_{CO_2}^{lim} \quad (117)$$

$Exe_{CO_2}(2029)$ : Excess CO<sub>2</sub> emissions in 2029 [gCO<sub>2</sub>/km]

$De_{CO_2}(2029)$ :  $CO_2$  emission debts in 2029 [gCO<sub>2</sub>/km]

$Cr_{CO_2}(2029)$ :  $CO_2$  emission credits in 2029 [gCO<sub>2</sub>/km]

$Exe_{CO_2}(t-1)$ : Transferred excess emissions (if positive) [gCO<sub>2</sub>/km]

$De_{CO_2}^{lim}(t)$ : Emission debt limit [gCO<sub>2</sub>/km]

The excess emissions from 2030 onwards are calculated as the difference between the average specific emissions of the new sales fleet and the specific CO<sub>2</sub> emissions target for 2030.<sup>617</sup>

$$Exe_{CO_2}(2030) = (CO_2^{av}(t) - CO_2^{lim}(2030)) * r_{total}^{sales}(t) \quad (118)$$

$Exe_{CO_2}(2030)$ : Excess CO<sub>2</sub> emissions in 2030 [gCO<sub>2</sub>/km]

$CO_2^{av}(t)$ : Average specific emissions [gCO<sub>2</sub>/km\*Truck]

$CO_2^{lim}(2030)$ : Specific CO<sub>2</sub> emissions target in 2030 [gCO<sub>2</sub>/km\*Truck]

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<sup>617</sup> European Commission (2018a), URL see Bibliography

$r_{total}^{sales}(t)$ : Total sales rate of trucks [Truck/Year]

A fine is imposed between 2025 and 2028 on manufacturers if the difference between emission credits and emission debts exceeds the emission debt limit, which is equivalent to the amount of emissions that results from the multiplication of number of heavy-duty vehicles of a year with five percent of the of the manufacturer's specific emission target in 2025. In 2029, a fine is imposed if the difference between emission debts and credits exceeds zero. From 2030 onwards, the manufacturer's specific emission target is taken as a reference to determine compliance. The manufacturers are penalized if the average specific emissions of a manufacturer's new sales fleet exceed the manufacturer's specific emission target.<sup>618</sup>

$$c_{CO_2}^{pen}(t) = \text{MAX} \left\{ 0, \frac{\text{Exe}_{CO_2}(t)}{r_{total}^{sales}(t)} \right\} * C_g^{pen} \quad (119)$$

$c_{CO_2}^{pen}$ : CO<sub>2</sub> penalty payment [€]

$C_g^{pen}$ : Excess emissions premium [€ per gCO<sub>2</sub>/km]

$c_{CO_2}^{pen}$ : Total excess emissions premium [€]

$r_{total}^{sales}(t)$ : Total sales rate of trucks [Truck/Year]

The following Table 18 lists all CO<sub>2</sub> regulation specific data needed for the equations in this chapter.

Specific CO <sub>2</sub> emissions target 2025 [gCO <sub>2</sub> /km*Truck]	CO <sub>2</sub> <sup>lim</sup> (2025)	466
Specific CO <sub>2</sub> emissions target 2030 [gCO <sub>2</sub> /km*Truck]	CO <sub>2</sub> <sup>lim</sup> (2030)	384

<sup>618</sup> European Commission (2018a), URL see Bibliography

Excess emissions premium [€ per gCO <sub>2</sub> /km]	C <sub>g</sub> <sup>pen.</sup> :	570
CO <sub>2</sub> emissions limit introduction year [Year]	T <sub>CO2</sub>	2025

Table 18 Parameter values for CO<sub>2</sub> regulation

The following Figure 22 shows the implementation of the calculation of the CO<sub>2</sub> emission credits and debts in System Dynamics.

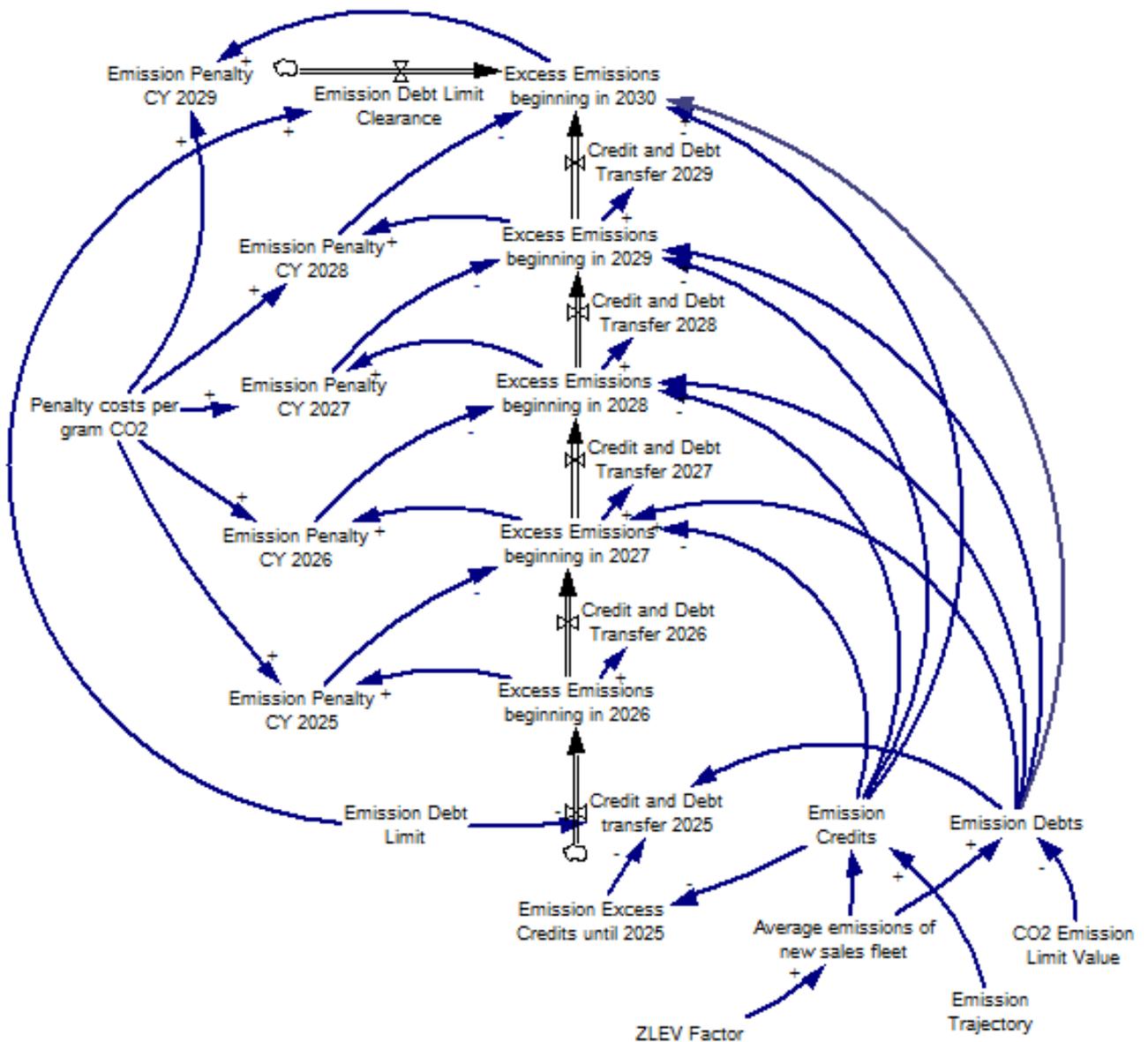


Figure 22 Calculation of the CO<sub>2</sub> emission credits and debts in System Dynamics

In a position paper of the European Automobile Manufacturers' Association (ACEA), truck manufacturers stated that they welcome CO<sub>2</sub> emission standards. However, they

argued that the CO<sub>2</sub> reduction target of 15 percent for 2025 is unrealistic to achieve as the trucks that will be used in 2025 are under development right now and proposed a target of 7 percent for 2025 and 16 percent for 2030.<sup>619</sup> Contrary to this position, the Committee on the Environment, Public Health and Food Safety of the European Parliament worked on a revised version of the original proposal and published a report suggesting to increase the CO<sub>2</sub> emissions reduction target even further to 20 percent for 2025 and 35 percent for 2030.<sup>620</sup> Furthermore, the CO<sub>2</sub> emissions reduction target for 2030 shall become legally binding.<sup>621</sup> In addition, the introduction of a minimum sales mandate for low- and zero-emission-vehicles was proposed.<sup>622</sup> In a final voting, the committee decided to increase the CO<sub>2</sub> emissions reduction targets to 20 percent for 2025 and 35 percent for 2030.<sup>623</sup> The super credit system is accompanied by a sales target for low- and zero-emission vehicles. The sales market shares for low- and zero-emission vehicles that have to be reached by manufacturers is set as 5 percent for 2025 and 20 percent for 2030.<sup>624</sup> The revised proposal has been backed by the European Parliament in a voting on November the 14<sup>th</sup>.<sup>625</sup> However, the targets will be transformed into applicable law after the negotiations between the three legislative bodies of the European Union, namely the European Parliament, the Council of the European Union and the European Commission, have taken place at the beginning of the next year.<sup>626; 627</sup> Due to this reason and due to time limitations, the proposal by the European Parliament with initial values for the CO<sub>2</sub> emission reduction targets has been used in this dissertation.

### 4.3 MODEL VALIDATION

Model validation is of particular importance and inevitable to gain confidence in the model's ability to reflect the dynamic behaviour of the system under consideration. The

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<sup>619</sup> ACEA (2018), p. 4

<sup>620</sup> Eickhout, B. (2018), p. 24

<sup>621</sup> Ibid., p. 44

<sup>622</sup> Ibid., p. 28

<sup>623</sup> Simon, F. (2018), URL see Bibliography

<sup>624</sup> Ibid.

<sup>625</sup> Lough, R. (2018), URL see Bibliography

<sup>626</sup> Ibid.

<sup>627</sup> europa.eu (2018), URL see Bibliography

validation procedure starts with the structure validity test, which is followed by the model behaviour validity test.<sup>628</sup> The structure validity test comprises direct structure tests, whose purpose is to test validity “by direct comparison of the model structure [...], mathematical equations and logical relationship with the available knowledge of the real systems”<sup>629</sup>, and structure-oriented behaviour tests, which try to assess qualitatively whether the predicted behaviour of the model matches the observed behaviour of the real system.<sup>630</sup>

### 4.3.1 STRUCTURE VALIDITY TESTS

The tests, which fall in the category of structure validity tests, are structure verification test, parameter verification test, extreme condition test, boundary adequacy test, and dimensional consistency test.<sup>631</sup> The structure verification test checks whether the mathematical equations reflect the relationships of the real system and the parameter verification test evaluates whether the parameters are in accordance with what is known from the literature.<sup>632</sup> The correctness of the mathematical equations and the parameters can be confirmed, as they are based on data from well-documented reports and studies. Each side of the equations has been tested for dimensional correctness in the dimensional consistency test.<sup>633</sup> The boundaries of the model are perceived as appropriate for the simulation of the market development, as they include all relevant stakeholders and the relationships between them.<sup>634</sup> The purpose of extreme condition tests is to assess the robustness of the model under extreme conditions, by comparing the predicted results with the anticipated results.<sup>635</sup> The model must behave under extreme conditions in a way that is expected from what is known about the system.

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<sup>628</sup> Bala et al. (2017), p. 133f.

<sup>629</sup> Ibid., p. 135

<sup>630</sup> Ibid., p. 136

<sup>631</sup> Ibid.

<sup>632</sup> Ibid., p. 136f.

<sup>633</sup> Ibid., p. 138

<sup>634</sup> Ibid., p. 137f.

<sup>635</sup> Ibid., p. 137

Extreme Condition Test 1:

Following variables have been chosen to perform the first extreme condition test. It is expected that a substantial increase in the diesel fuel price will deteriorate diesel truck and plug-in hybrid electric truck sales. The diesel fuel price is set to €10 per litre. From the graph can be seen that diesel sales drop to zero. The plug-in hybrid electric truck cannot gain any market share, as high diesel prices make its deployment unattractive (see Figure 23).

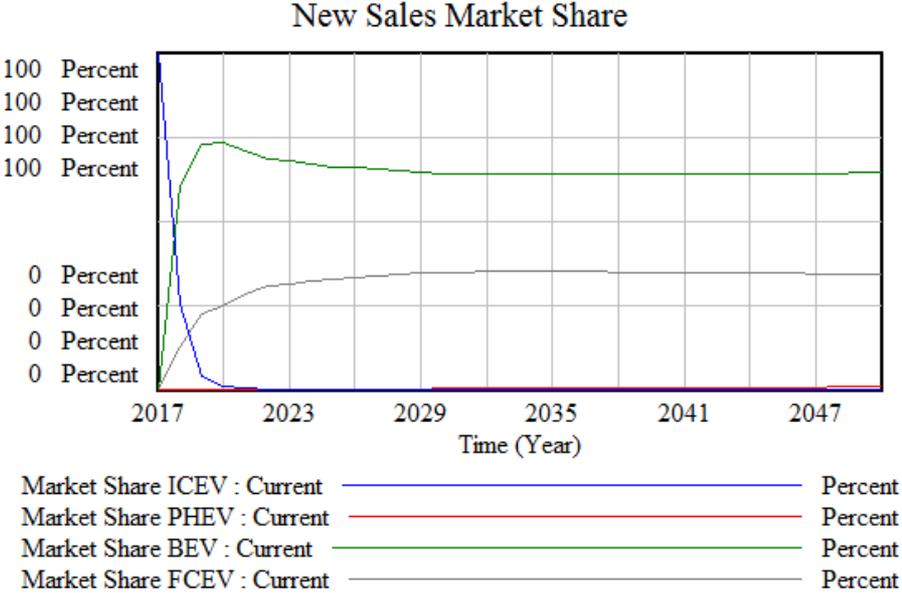


Figure 23 Extreme condition test 1

Extreme Condition Test 2:

In the second extreme condition test, the customers put greater emphasis on range, infrastructure availability and recharging time. The parameter weights governing their influence on utility are changed to extreme values. The extreme conditions test delivers a result with no market penetration of electric trucks (see Figure 24).



Figure 24 Extreme condition test 2

Extreme Condition Test 3:

In the last extreme condition test, two attributes of the fuel cell electric truck are improved considerably. The fuel consumption reduction is 10 percent per year, and the learning rate for fuel cell systems is 0.3. As the graph shows, the fuel cell technology becomes the dominant drivetrain option in urban freight transport (see Figure 25). This process is slow, as customers need to be convinced of the technology to consider it.

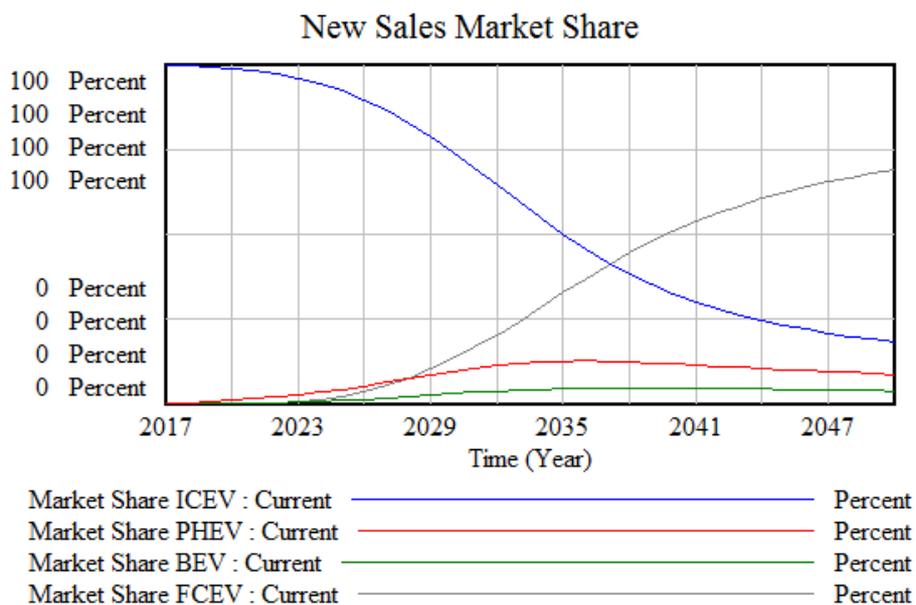


Figure 25 Extreme condition test 3

All three extreme condition tests are successfully passed, what enhances the confidence in the model's ability to depict the dynamic behaviour of the system realistically.

#### 4.3.2 BEHAVIOUR VALIDITY TESTS

Model validation is concluded with behaviour validity tests. These tests are performed only if the structural validity tests were successful.<sup>636</sup> They compare the predicted behaviour of the model with historical behaviour of the real system to discern whether the model is reliable or has defects, which need to be remedied.<sup>637</sup> As there are no historical sales figures for electric trucks, the behaviour validity test cannot be performed yet.

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<sup>636</sup> Bala et al. (2017), p. 139-141

<sup>637</sup> Ibid.

# 5. SCENARIO PLANNING AND RESULTS

In contrast to a System Dynamics model, which is primarily developed to understand the present behaviour of systems, scenario planning is a tool to grasp the possible futures.<sup>638</sup> Only the combination of scenario planning with a System Dynamics model results in a powerful tool with which the effectiveness of different policy strategies can be assessed. The high number of model input parameters makes it necessary to concentrate on parameters that are important or uncertain and to bundle them in scenarios, which have a high influence on the system behaviour or a high probability of occurrence.<sup>639</sup> The parameters that are varied in the context of the scenario analysis include diesel fuel price, diesel fuel consumption reduction, learning rates for batteries and fuel cells, the weights of the parameters purchase price, driving range and infrastructure availability, the CO<sub>2</sub> emissions limit, the marketing effort and subsidies for electric trucks. The dissertation considers several different scenarios, in which model parameters are varied to assess their impact on the diffusion of electric trucks. The Pro Electric Mobility and the Contra Electric Mobility Scenarios reflect the best case and the worst case scenarios for the diffusion of electric trucks. The parameters in the best case scenario have values that are most favourable for the diffusion of electric trucks, whereas in the worst case scenario the parameters have values that are least favourable for the diffusion of electric trucks.<sup>640</sup>

<b>Baseline Scenario:</b>	Values of all parameters reflect status-quo conditions or conditions that are predicted for the future
<b>Marketing Scenarios:</b>	Variation of the parameters for marketing and word-of-mouth
<b>Energy Price Scenarios:</b>	Variation of the diesel fuel price
<b>Learning Rates Scenarios:</b>	Variation of learning rate for batteries and fuel cells and the CO <sub>2</sub> emissions target for 2030

<sup>638</sup> Bala et al. (2017), p. 150

<sup>639</sup> Ibid., p. 156

<sup>640</sup> Sterman, J. D. (2000), p. 885

<b>Purchase Subsidy Scenario:</b>	Inclusion of electric truck purchase subsidies
<b>Public Infrastructure Scenario:</b>	Variation of infrastructure availability parameter weight, minimum number of battery charging points and hydrogen refuelling stations and inclusion of charger subsidies
<b>Pro Electric Mobility Scenario:</b>	Values of all parameters reflect a future environment that is favourable for electric trucks
<b>Contra Electric Mobility Scenario:</b>	Values of all parameters reflect a future environment that is not favourable for electric trucks

## 5.1 BASELINE SCENARIO

The Baseline Scenario reflects a sales forecast for trucks based on technological, economic and political conditions that are either existent in the UK or predicted for the future. In the Baseline Scenario, all parameters defined in the last sections are used throughout the simulation period. All truck types are offered at the beginning of the simulation period. There is no subsidisation of electric trucks by the government. The simulation run delivers expected results. There are hardly any sales of electric trucks until 2021. The diesel truck is still dominant in urban freight transport until 2050, but the market share gap is decreasing significantly, and electric trucks make up nearly 50 percent of the sales market share at the end of the simulation period (PHEV (28.5%), BEV (14.0%), FCEV (6.4%)). The first electric drivetrain technology to gain market shares is the plug-in hybrid electric truck as it has the lowest purchase price of all of the electric truck types and offers a fuel cost benefit compared with the diesel truck. The result shows clearly that the plug-in hybrid electric truck constitutes the steppingstone for the market success of electric trucks, as it initiates the process of battery cost reduction and battery energy development. Plug-in hybrid electric truck sales gain momentum towards the end of the next decade. This leads to a reduction in battery prices, which eventually makes battery electric trucks attractive to customers.

As can be seen from Figure 26, sales development of battery electric trucks follows the sales rate of plug-in hybrid electric trucks. After 2030, the fuel cell electric truck gains a foothold in the market. But the fuel cell electric truck is only able to occupy a market niche and the sales market share of the fuel cell electric truck only reaches 6.4 percent until 2050.

The sales market share of all electric truck types reaches 5.82 percent in 2025 (PHEV (4.48%), BEV (1.07%), FCEV (0.27%)) and is above the sales target of 5 percent for 2025 that has been proposed by the European Union.

However, the electric truck sales target of 20 percent for 2030 cannot be reached, as the sales market share in 2030 is 15.38 percent (PHEV (10.96%), BEV (3.36%), FCEV (1.06%)).

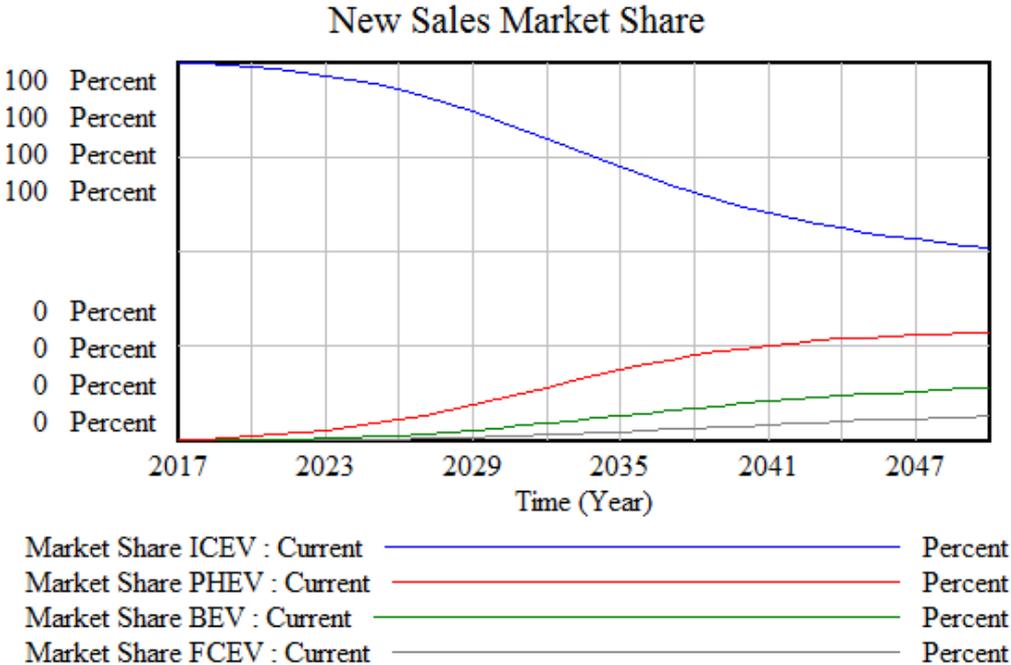


Figure 26 New sales market shares in Baseline Scenario

The share of electric commercial vehicles in the stock of all commercial vehicles changes slowly due to the long holding period of trucks (see Figure 27).

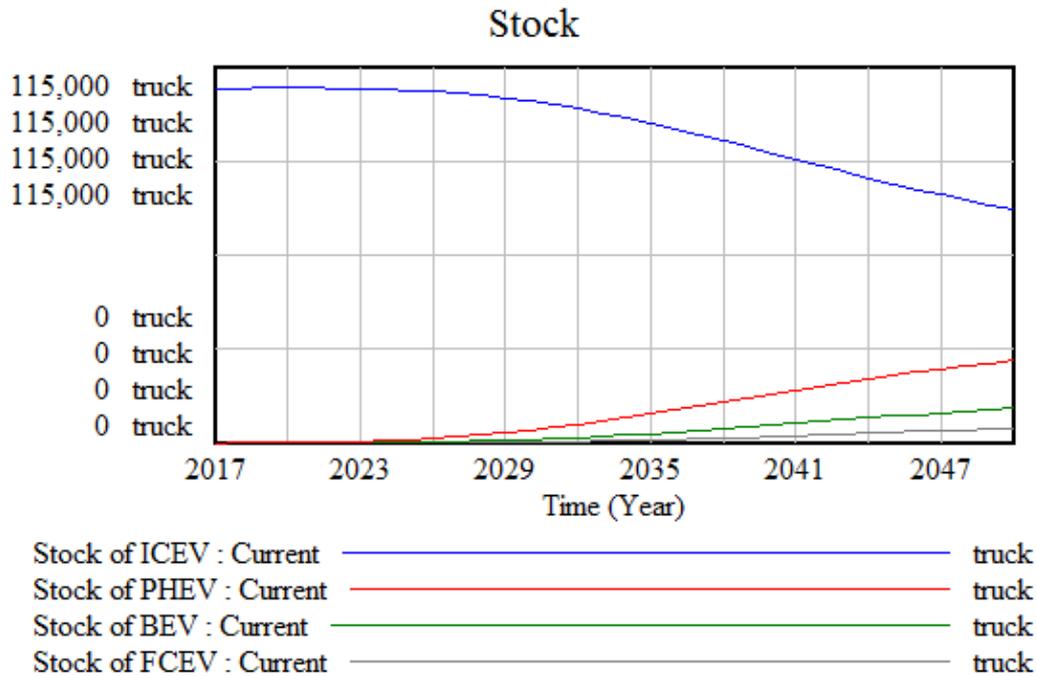


Figure 27 Stock in Baseline Scenario

Cost of batteries and thus the price of electric trucks decreases over the course of the simulation period due to economies of scale (see Figure 28).

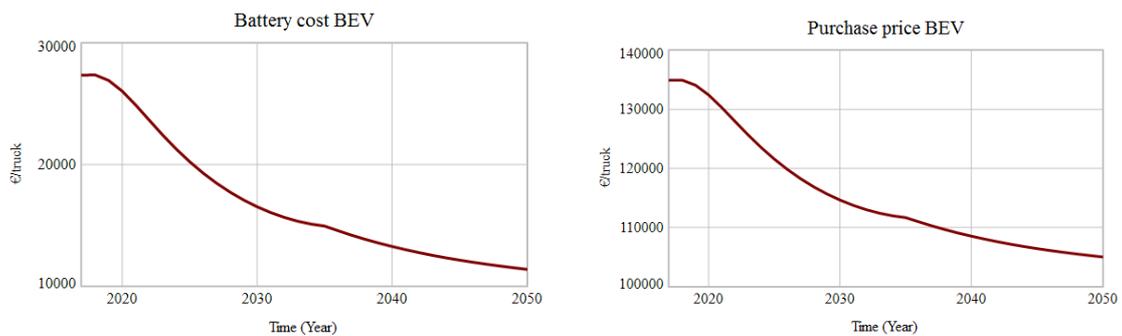


Figure 28 Battery cost and the purchase price of the battery electric truck in the Baseline Scenario

The fuel consumption of the diesel truck decreases as a result of efficiency measures, but the implementation of these measures makes the diesel truck more expensive (see Figure 29).

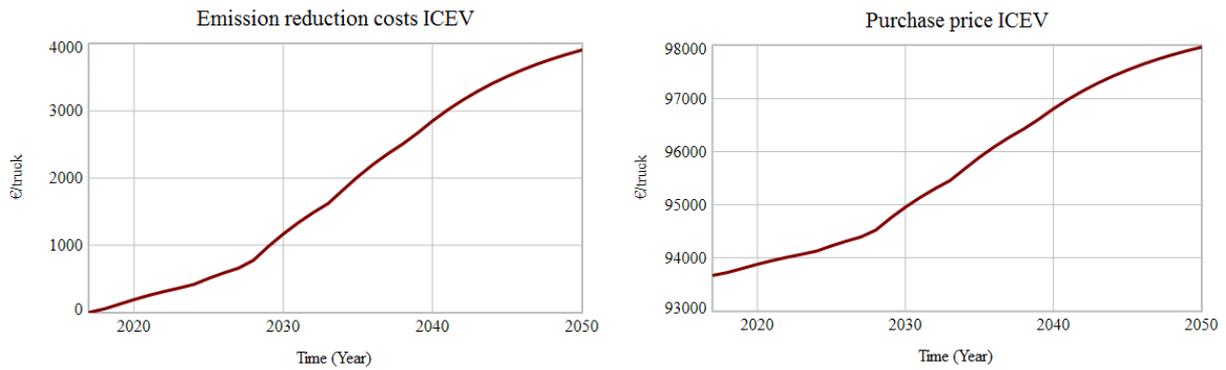


Figure 29 Emission reduction costs and the purchase price of the diesel truck

The willingness to consider electric trucks reaches its highest level very slowly. Truck manufacturers try to increase sales of electric trucks by higher marketing efforts after the tightening of the CO<sub>2</sub> emissions limit in 2030 (see Figure 30). The effect of higher marketing effort values on the diffusion of electric trucks will be investigated in the scenario analysis section.

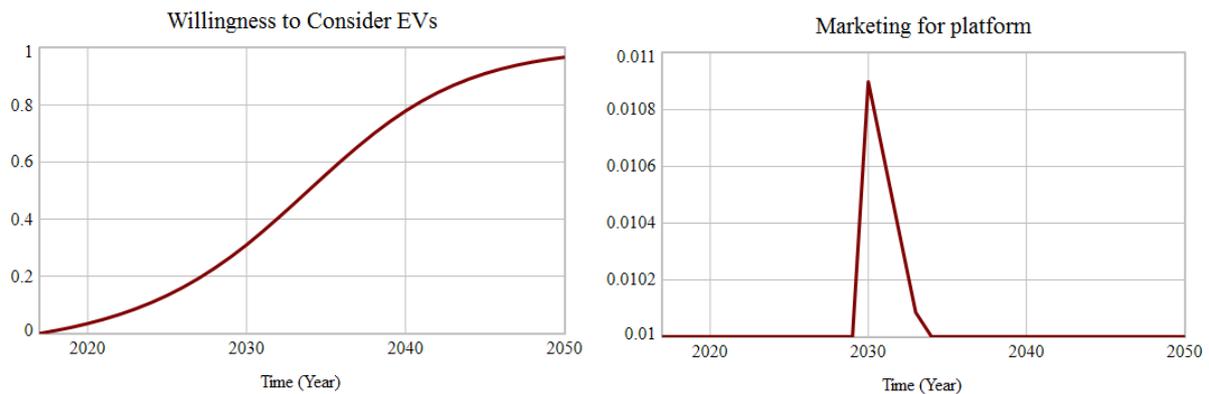


Figure 30 Willingness to Consider EVs in the Baseline Scenario

The driving range of battery electric trucks improves as higher battery capacities at a constant battery weight are achieved due to higher battery energy densities (see Figure 31). The battery capacity increase is limited to 100 kWh for urban freight transport, as otherwise the costs of the installed battery would rise and high driving ranges are not typical for urban delivery. Nevertheless, the battery electric truck still improves regarding the criteria electric driving range due to efficiency gains of the electric drivetrain, but with a smaller slope. Another strategy of manufacturers could be to lower the payload penalty by decreasing the battery weight at a constant battery capacity. The battery cost per kWh decreases to approximately 114 €/kWh in 2050.

This dissertation builds upon the assumption that lithium-ion batteries will be the dominant battery type until the end of the simulation period and does not consider the introduction of battery technologies like lithium-air, which could provide higher energy densities.

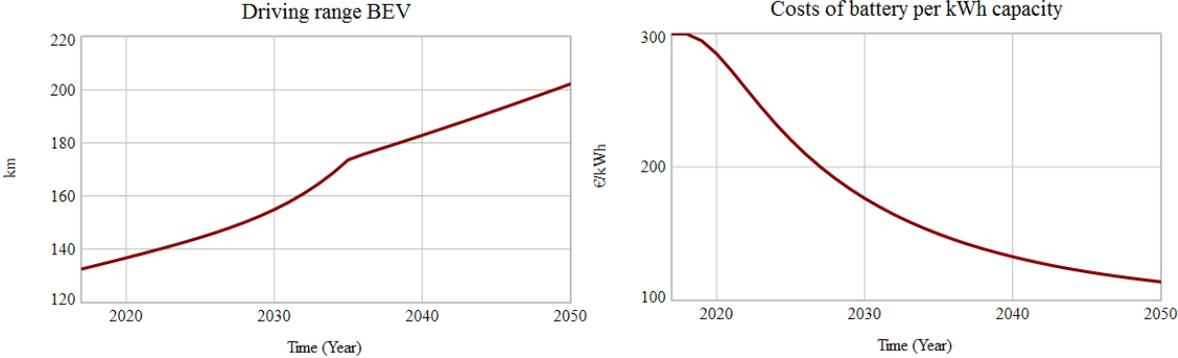


Figure 31 Driving range of the battery electric truck and battery cost per kWh

The CO<sub>2</sub> emissions limit of 384 g CO<sub>2</sub> per km for 2030 is achieved in 2034 but the average CO<sub>2</sub> emissions value of the new sales fleet continues to decrease to 270 g CO<sub>2</sub> per km in 2050 (see Figure 32) as the battery electric trucks and plug-in hybrid electric trucks reach maturity in technical and economic terms, which makes them serious alternatives to diesel trucks. The operating profit margin of truck manufacturers declines sharply due to CO<sub>2</sub> penalty payments after 2030, as truck manufacturers are able to comply with the emission standards of 2025. The target profit margin is reached very quickly after the sharp decline.

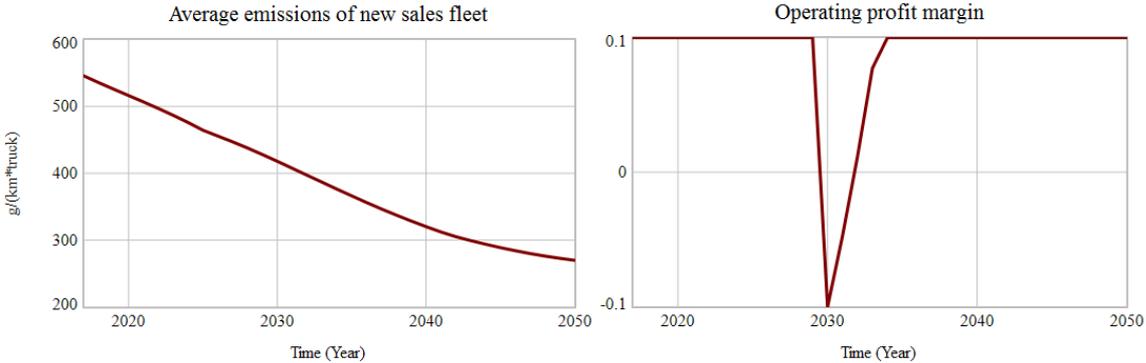


Figure 32 Average CO<sub>2</sub> emissions of new sales fleet and operating profit margin in the Baseline Scenario

The sales of electric trucks and the efficiency improvements of the diesel truck lead to an overall CO<sub>2</sub> reduction of 19.94 percent until 2050 (see Figure 33). The truck manufacturers generate CO<sub>2</sub> emission credits between 2019 and 2028. However, the manufacturers do not need these banked CO<sub>2</sub> emission credits as they do not generate any CO<sub>2</sub> emission debts in the following years up to 2030.

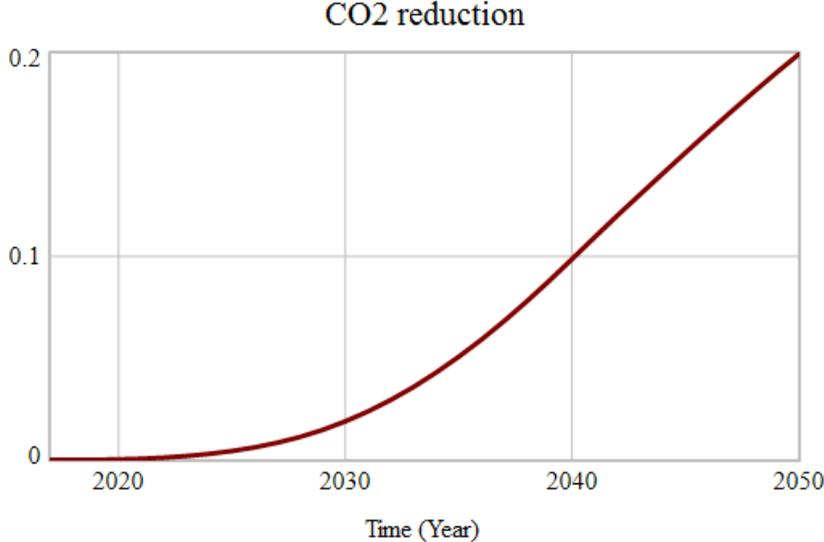


Figure 33 CO<sub>2</sub> emissions reduction in the Baseline Scenario

In the following, a sensitivity analysis is conducted with the weight parameters of the utility function used in the Baseline Scenario. This helps to understand the sensitivity of forecasts to the variation of model input parameters.<sup>641</sup> The parameter values, which are inherently subject to uncertainty in a forecasting model, are varied to check the robustness of the model. All other model parameters remain unchanged. As the parameter weights of the utility function are taken from a study about passenger customers, this section investigates how the variation of these parameters will affect the diffusion of electric trucks. Two different levels are chosen for the parameters. By this variation, it is aimed to imitate the behaviour of truck customers. The values for the parameters are found in Table 15 below.

<sup>641</sup> Bala et al. (2017), p. 127

<u>Variable</u>	<u>Parameter</u>	<u>Cars</u>	<u>Trucks</u>	
Purchase Price	$\beta_1$	-0.0519	-0.075	-0.10
Energy Costs per 100 km	$\beta_2$	-0.0480	-0.06	-0.08
Driving Range (logarithmic)	$\beta_4$	0.4939	0.3	0.1
CO <sub>2</sub> emissions (logarithmic)	$\beta_5$	-0.0489	-0.03	-0.01
Recharging Time (logarithmic)	$\beta_7$	-0.0651	-0.05	-0.03
Infrastructure Availability (logarithmic)	$\beta_8$	0.2203	0.15	0.05

Table 19 Variation of utility function parameter weights

As purchase price and energy costs are the key drivers in the purchase decision of truck customers, the influence of the parameter weights of these costs in the utility function is increased relative to the weights of the passenger car study. The increase in the influence of the purchase parameter weight leads to a decrease in the diffusion of electric trucks, as they are more expensive than the diesel truck (see Figure 34).

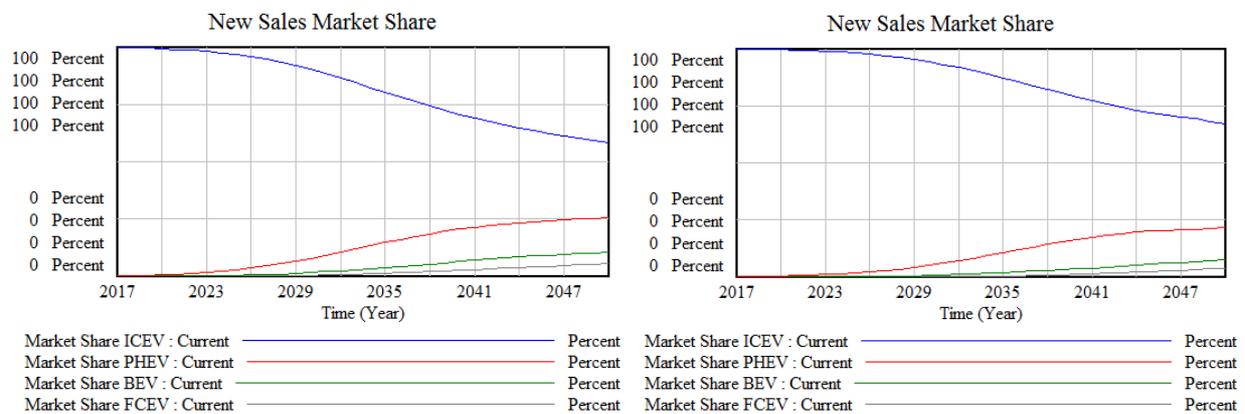


Figure 34 Variation of the purchase price parameter weight

The increase of the influence of the energy cost parameter weight makes battery electric trucks and plug-in hybrid electric trucks more attractive, as they consume less energy per km than the diesel truck (see Figure 35).

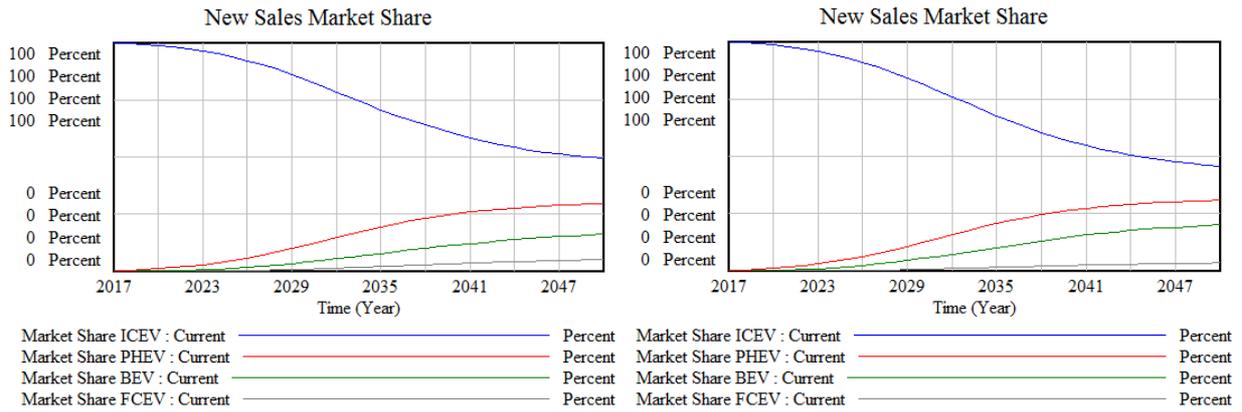


Figure 35 Variation of the energy cost parameter weight

As the batteries and the hydrogen tanks are scaled to offer a range of 133 kilometres and this is sufficient for most of the urban freight operations, the driving range limitation of electric trucks might be less crucial than for passenger cars. Therefore the influence of the driving range weight is lowered to check its effect on the diffusion of electric trucks. The decrease in the influence of the driving range parameter weight makes the battery electric truck and fuel cell electric truck more attractive, as their driving range is limited due to the hydrogen tank size and battery capacity limitations (see Figure 36).

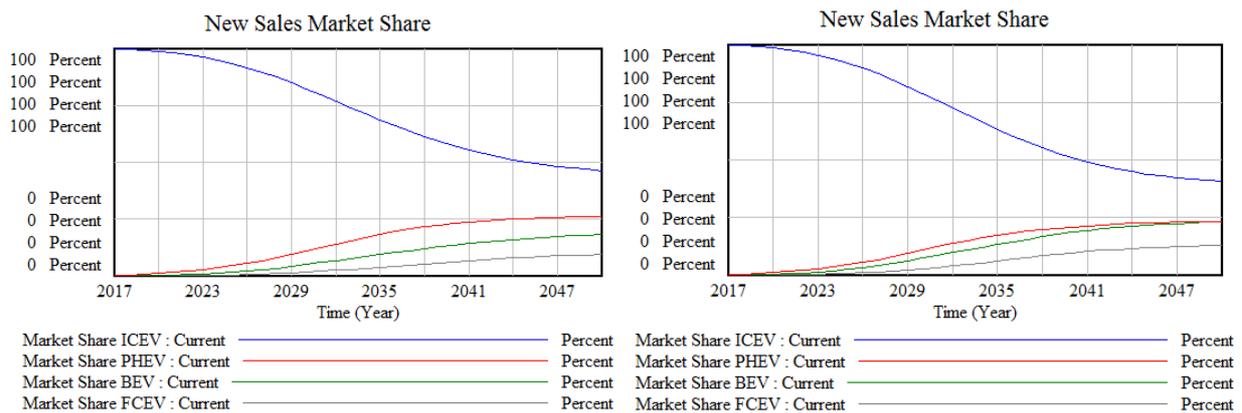


Figure 36 Variation of the driving range parameter weight

The environmental consciousness of truck operators is assumed to be lower<sup>642</sup>, as economic considerations largely drive the purchase decision. Furthermore, fuel

<sup>642</sup> Baster et al. (2014), p. 26

economy standards are in place for passenger and light-duty vehicles in most countries of the world, whereas fuel consumption standards for heavy goods vehicles will be introduced in 2025. Additionally, a sales ban on diesel trucks is applied in different European countries for the passenger and light goods vehicle markets at first. In light of an absence of driving or sales bans for heavy goods vehicles, customers will not attach great importance to environmental considerations. Thus, the influence of the parameter weight of CO<sub>2</sub> emissions is lowered. The decrease in the influence of the emissions parameter weight does not alter the diffusion of electric trucks significantly (see Figure 37).

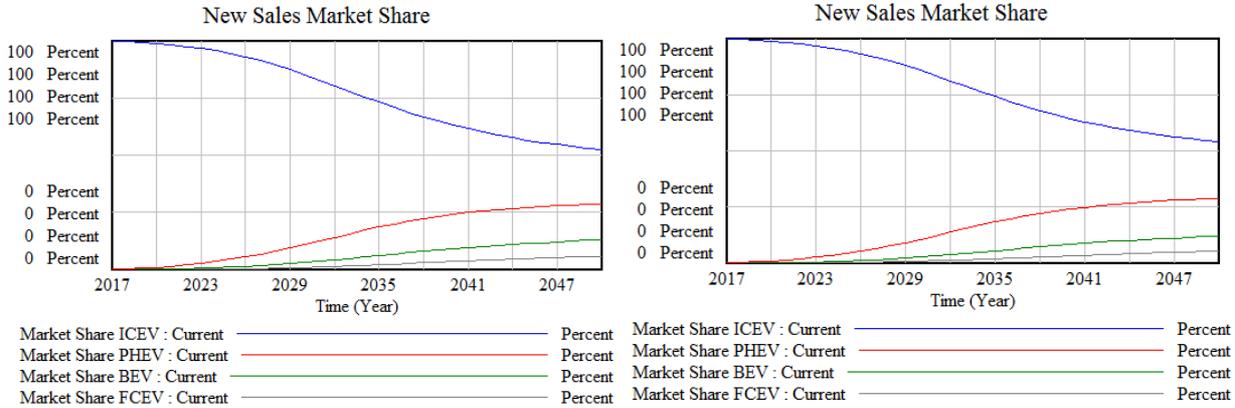


Figure 37 Variation of the CO<sub>2</sub> emissions parameter weight

The scheduled return-to-base operations of commercial vehicles make recharging time a less critical issue for operators. Therefore, the influence of the recharging parameter weight on the utility is lowered. The decrease in the influence of the recharging time parameter weight makes the battery electric truck more attractive and increases its new sales market share (see Figure 38).

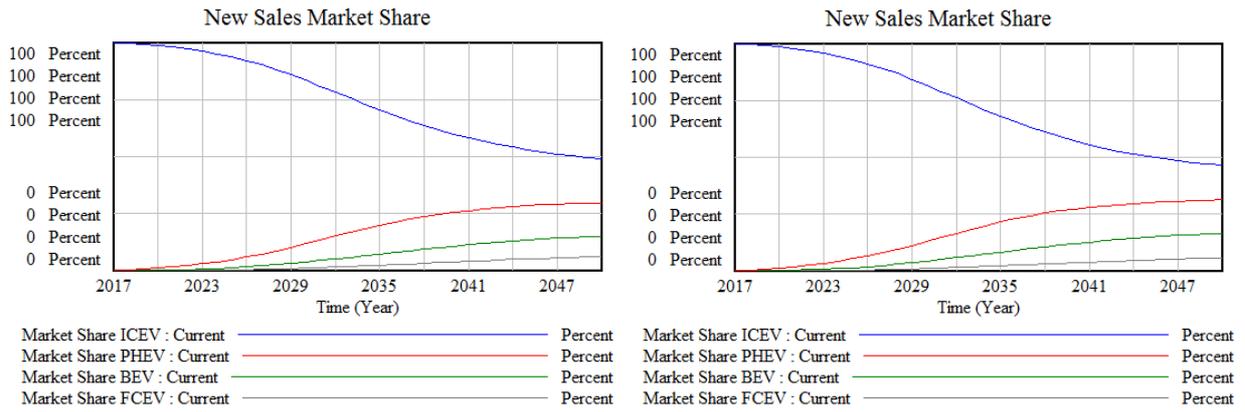


Figure 38 Variation of the recharging time parameter weight

A lack of public charging infrastructure is a huge barrier to adoption in the passenger car market, as customers are used to driving long distances without refuelling. In urban freight transport, however, the return-to-base operations and the associated predictability of charging times make infrastructure availability a less critical issue. Therefore, the influence of the infrastructure availability weight on utility is lowered for truck customers. However, the weight is not unimportant as not every truck operator will have access to depot charging. The decrease in the influence of the infrastructure availability parameter weight does not significantly alter the diffusion rates of electric trucks (see Figure 39).

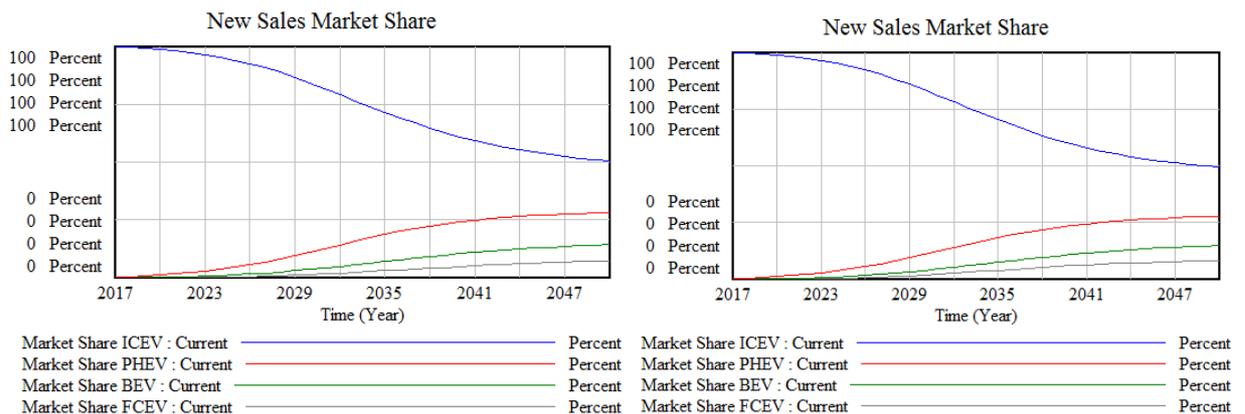


Figure 39 Variation of the public charging infrastructure parameter weight

The sensitivity simulation in System Dynamics with 200 simulation runs for the parameter weights for purchase price (see Figure 40) and CO<sub>2</sub> emissions (see Figure 41) shows clearly that a variation of the parameter weight for purchase price has a

much greater effect on the diffusion of electric trucks than the variation of the parameter weight for CO<sub>2</sub> emissions. For the simulation runs, the maximum value for the purchase price parameter weight is set to -0.0519 and the minimum value is set to -0.10 and the maximum value for the CO<sub>2</sub> emissions parameter weight is set to -0.01 and the minimum value is set to -0.0489. The confidence bounds of 50%, 75%, 95%, and 100% are shown in different colours.

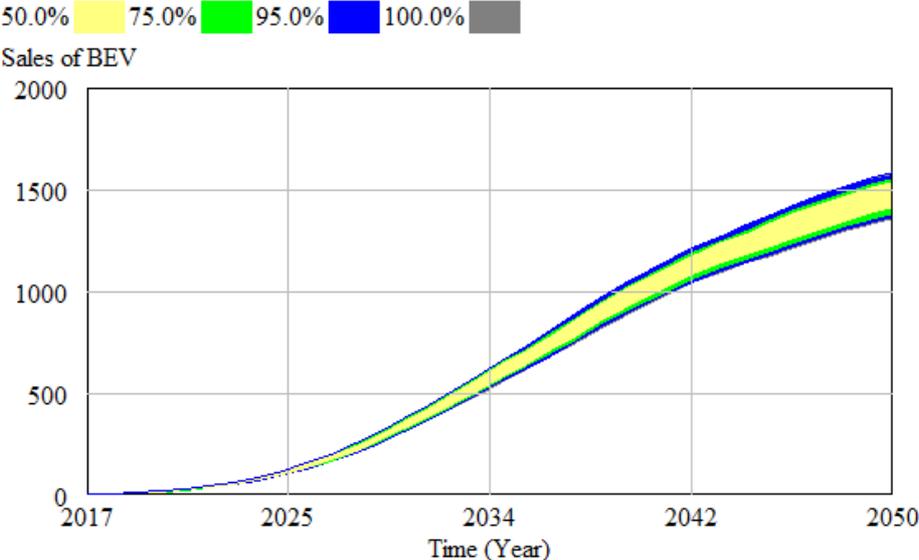


Figure 40 Sensitivity simulation for the CO<sub>2</sub> emissions parameter weight

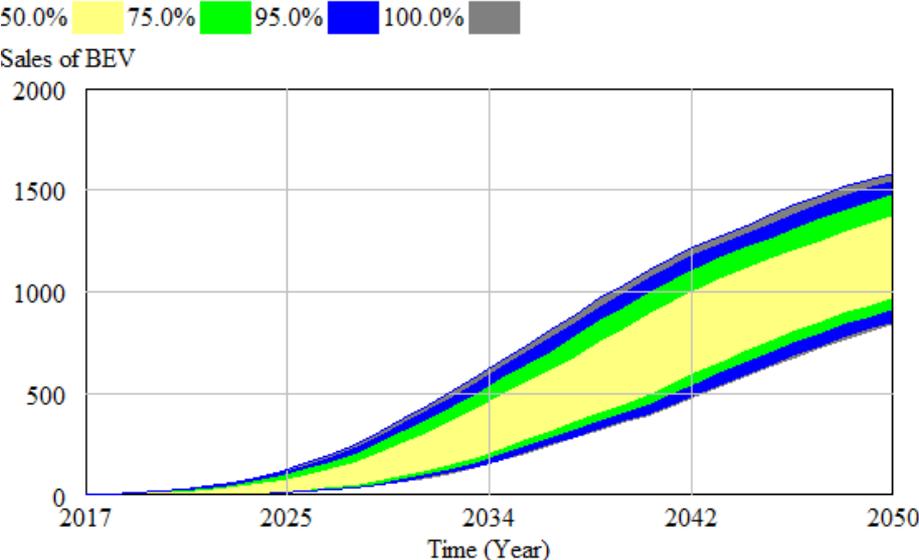


Figure 41 Sensitivity simulation for the purchase price parameter weight

## 5.2 MARKETING SCENARIOS

A lack of marketing for electric trucks can hamper the diffusion process. The reluctance of truck customers to invest in a new drivetrain technology can be overcome by highlighting the potential benefits of these technologies. Fleet operators are generally skeptical about the fuel saving potential and the range capability of electric trucks.<sup>643</sup> Thus, demonstration projects from manufacturers could proof the fuel saving benefits of electric trucks and limit the range anxiety of customers. Furthermore, trials with electric trucks have shown that truck drivers appreciated the acceleration and silence of these vehicles.<sup>644</sup> These benefits of electric trucks will be spread to other truck drivers by word-of-mouth communication.

To capture these effects, two sub-scenarios have been defined (see Table 20). In the Aggressive Marketing Scenario, the effectiveness of marketing and word-of-mouth communication is higher than in the Baseline Scenario, whereas the opposite is true for the Conservative Marketing Scenario.

The results of these scenarios underline the importance of information frictions for the diffusion of electric trucks (see Figure 42). Marketing and word-of-mouth effects lead to a decline in the uncertainty about the benefits of electric trucks. As a consequence, a higher percentage of customers consider these technologies in their next purchase decision.

Sub-Scenario	Effectiveness of marketing and promotion for EVs [-]	Effectiveness of word-of-mouth contacts with drivers of EVs [-]	Word-of-mouth about EVs among drivers of ICEVs [-]
1 Aggressive Marketing	0.05	0.35	0.25
2 Conservative Marketing	0.005	0.15	0.05

Table 20 Parameter values of Marketing Scenarios

<sup>643</sup> Kay, D. and Hill, N. (2012), p. 30

<sup>644</sup> Quak et al. (2016), p. 8

- $\alpha_{EV}$ : Effectiveness of marketing and promotion for EVs [-]
- $\vartheta_{EV}$ : Effectiveness of word-of-mouth contacts with drivers of EVs [-]
- $\vartheta_{ICE}$ : Word-of-mouth about EVs among drivers of ICEVs [-]

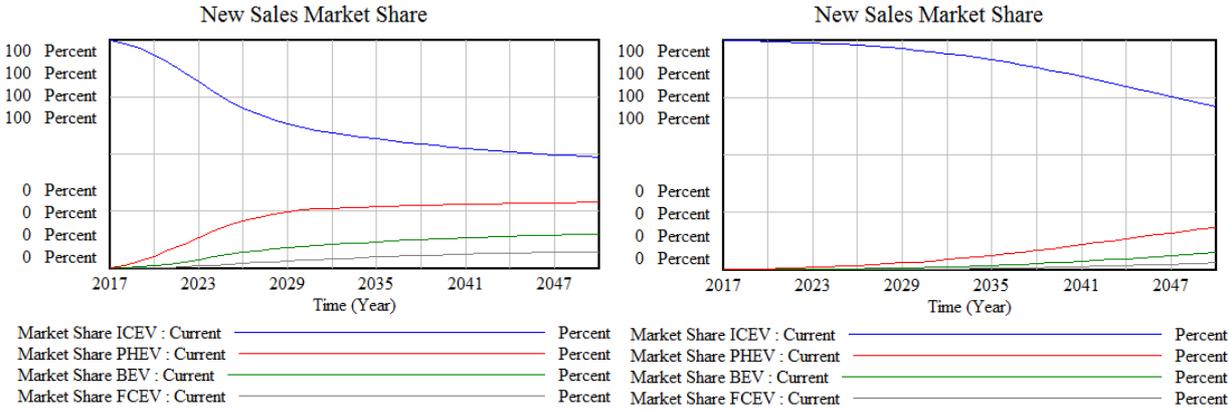


Figure 42 New sales market shares in Marketing Scenarios

### 5.3 ENERGY PRICE SCENARIOS

Operating costs are one of the most important purchase criteria for trucks. In the following, the fuel price growth rates, which are used in the scenarios, are described. Historical fuel prices cannot simply be projected into the future, as future prices depend on many factors that are unknown like “future economic growth rates across the world, development of new technologies, global climate change policies, technological developments and strategies of resource holders.”<sup>645</sup> Two Energy Price Scenarios are defined on the basis of fuel price assumptions of the report from the Department for Business, Energy & Industrial Strategy.<sup>646</sup> The diesel price, which the customer has to pay at the fuelling station, is determined by different elements. The government duty and tax account for the largest share of the diesel price, followed by the cost of diesel on the open market and the costs and profit of the wholesaler and retailer.<sup>647</sup> There is a link between the price of crude oil per barrel and the pump price of diesel. Based on historical data, a rise in crude oil prices by \$2 per barrel has led to

<sup>645</sup> Department for Business, Energy & Industrial Strategy (2016b), p. 2

<sup>646</sup> Ibid., p. 5-12

<sup>647</sup> UKPIA (2016), p. 1

an average pump price increase of one pence per litre at a constant currency exchange rate.<sup>648</sup>

**High Price Assumption:** Price per barrel of crude oil increases to \$120. This corresponds to a diesel pump price of £1.2907 or €1.4653 respectively (Pro Electric Mobility Scenario)

**Low Price Assumption:** Price per barrel of crude oil decreases to \$50. This corresponds to a diesel pump price of £0.9408 or €1.0681 respectively (Contra Electric Mobility Scenario)

It is assumed that the electricity price rises with increasing usage of renewable energy sources, as electricity suppliers need to invest in renewables. Therefore, the electricity price rises one percent per annum in both sub-scenarios.

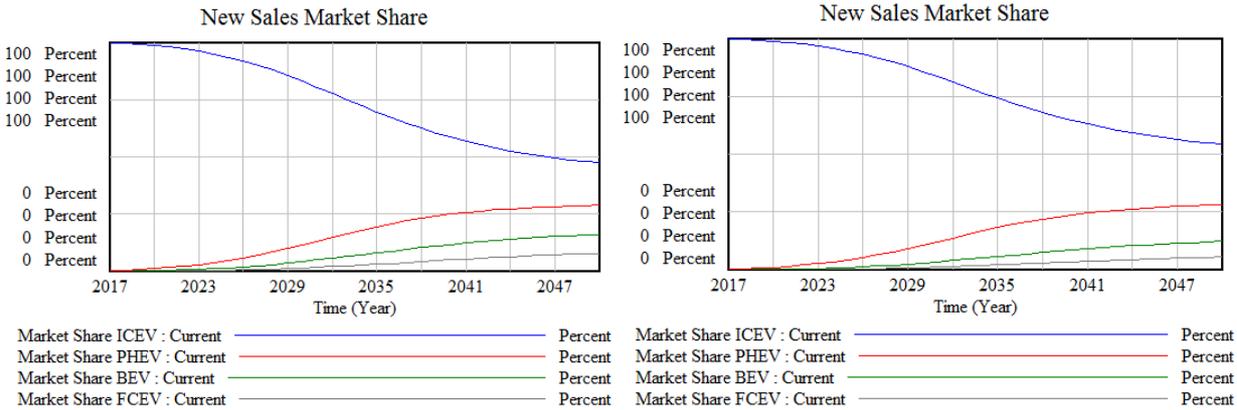


Figure 43 New sales market shares in Energy Price Scenarios

The results show that the freight market is sensitive to diesel fuel price changes (see Figure 43). As expected, the battery electric truck is profiting the most from a high diesel fuel price followed by the fuel cell electric truck. The new sales market share of battery electric trucks is four percent higher in 2050 in the High Price Assumption Scenario than in the Low Price Assumption Scenario.

<sup>648</sup> UKPIA (2016), p. 2

## 5.4 LEARNING RATE SCENARIOS

It is to be expected that the implementation of a CO<sub>2</sub> standard will lead to an increase in investments in research and development of electric trucks by the truck manufacturers.<sup>649</sup> Thus, the learning rates for the battery and fuel cell system will be higher in the presence of stricter CO<sub>2</sub> standards.<sup>650</sup> This scenario investigates how higher learning rates alter the diffusion rates of electric trucks. In scenario one, an aggressive learning rate in combination with a tight CO<sub>2</sub> standard is defined, whereas in scenario two a conservative learning rate in combination with a weak CO<sub>2</sub> standard is defined (see Table 21). The CO<sub>2</sub> emissions reduction target shows the value that has to be achieved in 2030.

Sub-Scenario	Learning rate battery [-]	Learning rate fuel cell [-]	CO <sub>2</sub> emissions reduction target 2030 [-]
1 Aggressive Learning Rate	0.20	0.25	35%
2 Conservative Learning Rate	0.10	0.15	15%

Table 21 Parameters of Learning Rate Scenarios

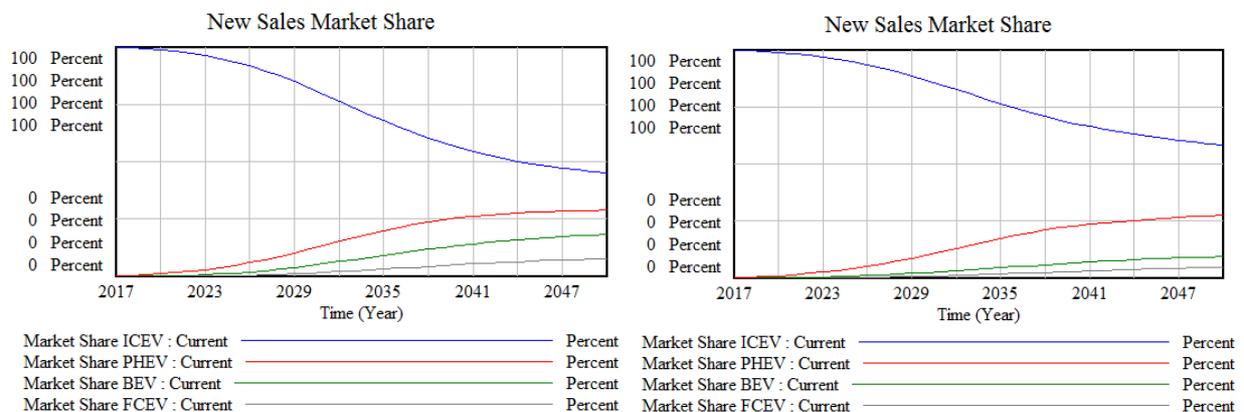


Figure 44 New sales market shares in Learning Rate Scenarios

<sup>649</sup> AEA (2009), p. 27

<sup>650</sup> Ibid.

A higher learning rate for batteries combined with a tight CO<sub>2</sub> emissions limit is a guarantee for faster diffusion of battery electric trucks. The diffusion of fuel cell electric trucks is also affected by a high learning rate but to a lesser extent. In the scenario with a low learning rate and a weak CO<sub>2</sub> emissions limit, the battery electric truck is able to gain a strong foothold in the market (see Figure 44).

### 5.5 PURCHASE SUBSIDY SCENARIOS

The high upfront cost of the electric truck is one of the main barriers to its diffusion in the market. Small margins in the transport sector impede investments that pay off later in time.<sup>651</sup> The battery and fuel cell system costs are key factors that will determine the success of electric mobility in road freight transport. The battery and fuel cells costs are still too high, but economies of scale will drive down their cost. This chapter investigates whether and to what extent purchase subsidies, which reduce the initial capital outlay, can initiate and accelerate the diffusion process (see Table 22).

Sub-Scenario	Subsidy PHEV	Subsidy BEV	Subsidy FCEV	Timeframe
1 Early Subsidy	€5,000	€10,000	€10,000	2017-2023
2 Late Subsidy	€5,000	€10,000	€10,000	2024-2029

Table 22 Parameters of Purchase Subsidy Scenarios

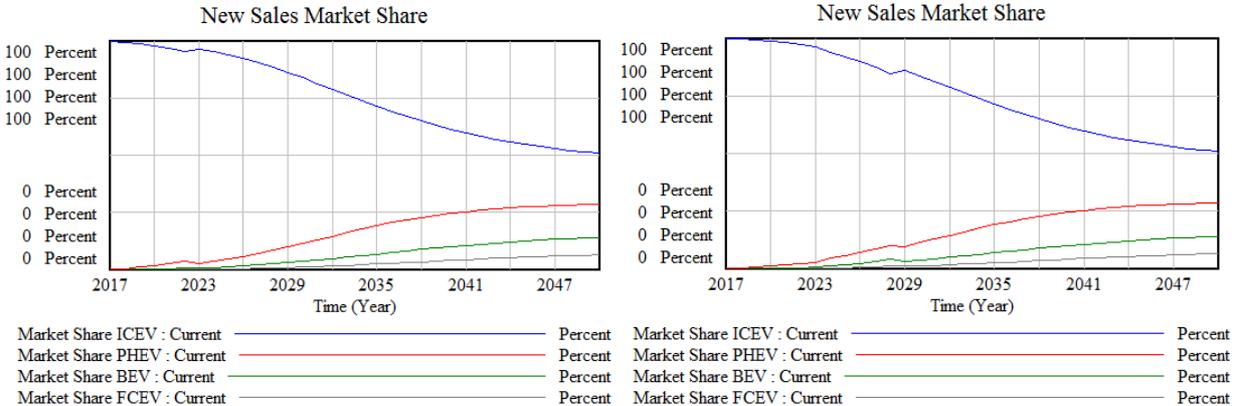


Figure 45 New sales market shares in Purchase Subsidy Scenarios

<sup>651</sup> Kay, D. and Hill, N. (2012), p. 7

The results show that subsidies have a positive impact on the sales rates of electric trucks in the early phase of the diffusion (see Figure 45). With the phase-out of the subsidy program, the purchase probability of electric trucks decreases. The rise in the sales market share of electric trucks is steeper in the Late Purchase Subsidy Scenario. The reason for this is that the value of the willingness to consider electric trucks is very low in the starting phase of the diffusion and a portion of the subsidy remains unutilized. Thus, a later introduction year of purchase subsidies increases the diffusion rates of electric trucks stronger, although the subsidies are time-restricted (see Figure 45).

## **5.6 PUBLIC INFRASTRUCTURE SCENARIOS**

Interviews with fleet operators in London revealed that a lack of sufficient public charging and hydrogen refuelling infrastructure is a significant barrier to the uptake of electric trucks.<sup>652</sup> Therefore different scenarios are developed to investigate the impact of charging and refuelling infrastructure on the diffusion results (see Table 23).

### **No opportunity to install in-depot infrastructure in London**

In this sub-scenario, truck operators do not invest in depot-charging infrastructure due to following reasons: fleet operators either do not have the financial resources to install charging points at the depot or do not have enough space for the charging points.<sup>653</sup> Some of the fleet operators only lease their depot for a short time and do not own it, why they do not want to invest in infrastructure.<sup>654</sup> Therefore they rely on the provision of public battery charging points. These aspects are expressed in this scenario by increasing the importance of the infrastructure availability parameter.

### **Subsidies to install in-depot infrastructure in London**

The weight of the public infrastructure availability is lowered, as operators rely on their depot charging infrastructure and the government supports the installation of charging infrastructure with subsidies until 2030. The minimum number of charging points and

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<sup>652</sup> Lyons, S. and Chatterji, P. (2016), p. 4

<sup>653</sup> Ibid., p. 27

<sup>654</sup> Ibid.

hydrogen refuelling stations remains unchanged this scenario. The reason, why the diffusion of plug-in hybrid electric trucks is at a high level compared to the other electric trucks in scenario one is that a plug-in hybrid electric truck can rely on the petrol stations infrastructure. The lack of hydrogen refuelling stations is a major barrier to adoption in a scenario, in which customers put a great emphasis on public infrastructure availability.

Sub-Scenario	Infrastructure availability parameter	Minimum number of battery charging points	Minimum number of hydrogen refuelling stations	Subsidy for battery charging point for a BEV	Subsidy for battery charging point for a PHEV
No opportunity	0.8	150	25	-	-
Charger Subsidies	0.05	150	10	€5,000 (2017-2024)	€1,050 (2017-2024)

Table 23 Parameters for Public Infrastructure Scenarios

The results show that a subsidy for charging infrastructure in scenario two increases the diffusion of battery electric trucks (see Figure 46). In scenario two, the plug-in hybrid electric truck cannot increase the sales market share compared with the Baseline Scenario significantly despite the exclusion of charger costs. The reason for this is that charger costs for the plug-in hybrid electric truck are relatively low, and the subsidy phases out after 2029.

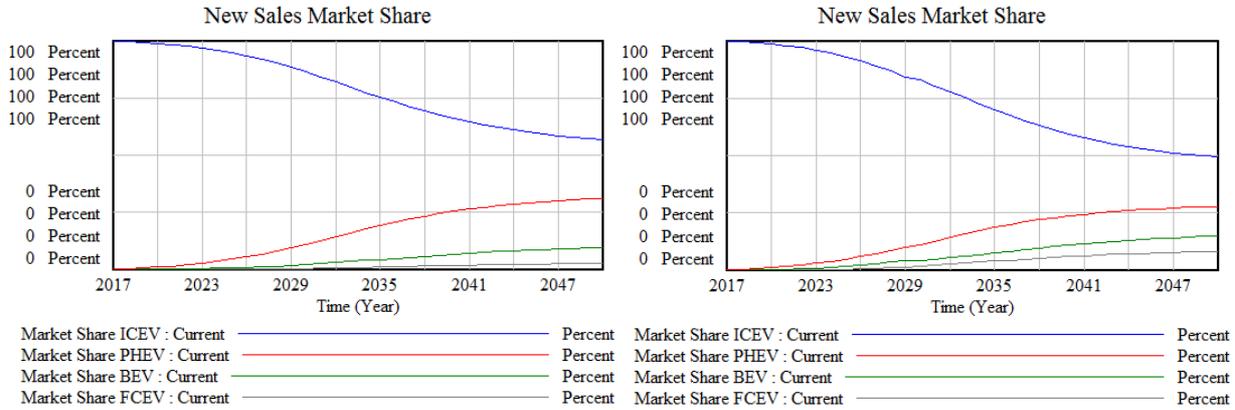


Figure 46 New sales market shares in Public Infrastructure Scenarios

## 5.7 PRO ELECTRIC MOBILITY SCENARIO

The Pro Electric Mobility Scenario is characterized by a slow pace of diesel truck efficiency improvements. Manufacturers and transport companies do not want to invest in a truck that possibly will be banned from city centres in the near future. The government uses both technology-push and demand-pull policies to foster the diffusion of electric trucks. The government aims to stimulate research and development by technology-push measures like formulating research priorities, direct public funding, technology standards, corporate technology development agreements and initiation and stimulation of networks and collaborative R&D partnerships.<sup>655</sup> These measures lead to high learning rates for batteries and fuel cells and efficiency gains for electric motors and fuel cell systems. It is common that governments use temporary subsidies as a demand-pull measure to support the uptake of energy innovations. Once the tipping point is reached, from which on the diffusion process gets self-sustained, the subsidies are phased out.<sup>656</sup> In this scenario, the government subsidises battery electric trucks and fuel cell electric trucks with a grant of €10,000 and the plug-in hybrid electric truck with €5,000 from 2022 until 2029 and stops the subsidisation then. Transport companies do not have to burden the costs of charging infrastructure at their depots from 2022 until 2029, as it is subsidised as well. It is assumed that customers have a greener procurement policy, as some municipalities have introduced Zero Emission Zones in inner cities and city crossing bans for noisy trucks. In addition to that, innovators in the trucking business are willing to pay a price premium for electric trucks. A lower influence of the weight of the purchase price on the utility reflects this. Furthermore, customers evaluate the driving range capabilities and the lack of public infrastructure options for electric trucks less negatively. A portion of the truck customers care more about the environmental friendliness of their vehicle due to corporate responsibility and image considerations, what results in a higher influence of the weight of the CO<sub>2</sub> emissions output on the utility. Given the green customer behaviour, manufacturers want to be the pioneers in electric mobility and are using marketing as a means to promote electric trucks more aggressively. This also helps them to reduce the burden of greenhouse gas penalty payments. The diesel fuel price peaked due to global oil shortage and a higher fuel taxing by the government,

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<sup>655</sup> Turkenburg, W. (2002), p. 14f.

<sup>656</sup> Ibid., p. 141

which uses this financial instrument to support electric mobility in freight transport. Fleet owners use Vehicle-to-Grid (V2G) technology to sell electricity to utilities when their trucks are not in operation.<sup>657</sup> The electricity price is not increased in the Pro-Electric-Mobility Scenario to capture the decrease in operational costs in the model as a result of Vehicle-to-Grid usage. Vehicle-to-Grid technology is especially attractive for truck companies, as the scheduled operation of trucks allows the planning of the electricity transaction.<sup>658</sup> The following Table 24 lists all parameters that are changed in favour of electric trucks in the Pro Electric Mobility Scenario.

High diesel fuel price assumption + fuel tax	Diesel fuel price: €1.6
Slow internal combustion engine efficiency improvements	High adjustment time for fuel consumption reduction: 15 years
High learning rates for batteries	0.2
High learning rates for fuel cells	0.25
Purchase price weight	-0.03
Driving range weight	0.1
Infrastructure and service station availability weight	0.1
CO <sub>2</sub> emissions parameter weight	-0.1
Marketing efforts	0.05
Subsidies for EVs from 2022 until 2029	€10,000 per truck (BEV, FCEV) €5,000 per truck (PHEV)
Subsidies for battery charging points from 2022 until 2029	€5,000 (BEV) €1,050 (PHEV)

Table 24 Parameter values in the Pro Electric Mobility Scenario

As expected, the battery electric truck becomes the dominant truck type at the end of the next decade (39.31%), but electric trucks are not able to entirely replace the diesel truck. There is still a portion of customers, which relies on diesel trucks to accomplish their transport tasks (22.83%). Fuel cell electric trucks (17.13%) and plug-in hybrid electric trucks (20.73%) also find a customer base (see Figure 47).

<sup>657</sup> Barry, K. (2012), URL see Bibliography

<sup>658</sup> Ibid.

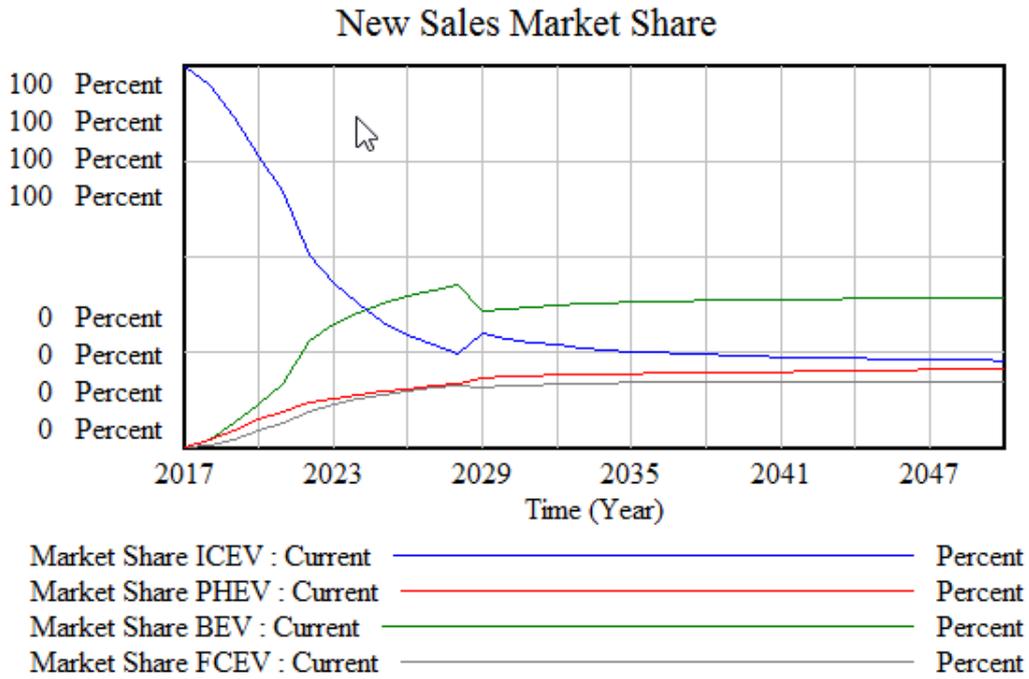


Figure 47 New sales market shares in the Pro Electric Mobility Scenario

The vehicle production costs and the purchase price of battery electric trucks are lower compared with the Baseline Scenario, what is attributable to lower battery cost and subsidies (see Figure 48).

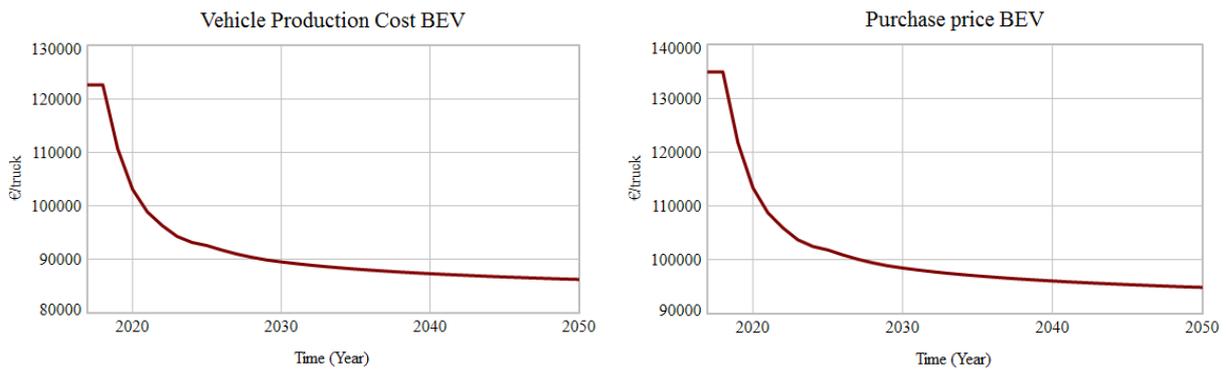


Figure 48 Production costs and the purchase price of the battery electric truck in the Pro Electric Mobility Scenario

The battery technology improves fast concerning cost per kWh and energy densities. A kWh battery capacity costs around €59.3 in 2050 and the energy density reaches its

technological maximum of 0.315 kWh per kg at the end of the simulation period (see Figure 49). The driving range improves very fast.

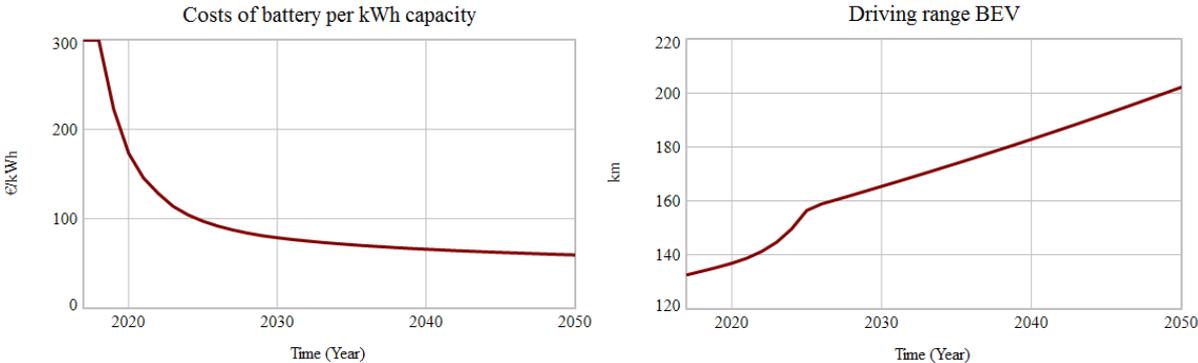


Figure 49 Battery cost and energy density in the Pro Electric Mobility Scenario

Truck manufacturers do not pay any CO<sub>2</sub> penalty payments due to the fast diffusion of electric trucks in the market. Thus, the deterioration of the operating profit margin of manufacturers is avoided. The average CO<sub>2</sub> emissions of the new sales fleet constantly decrease during the simulation period. This decline in CO<sub>2</sub> emissions does not come to a halt after the average CO<sub>2</sub> emissions of the new sales fleet have reached the CO<sub>2</sub> emissions limit, but continues even without any further tightening of the CO<sub>2</sub> emissions limit (see Figure 50).

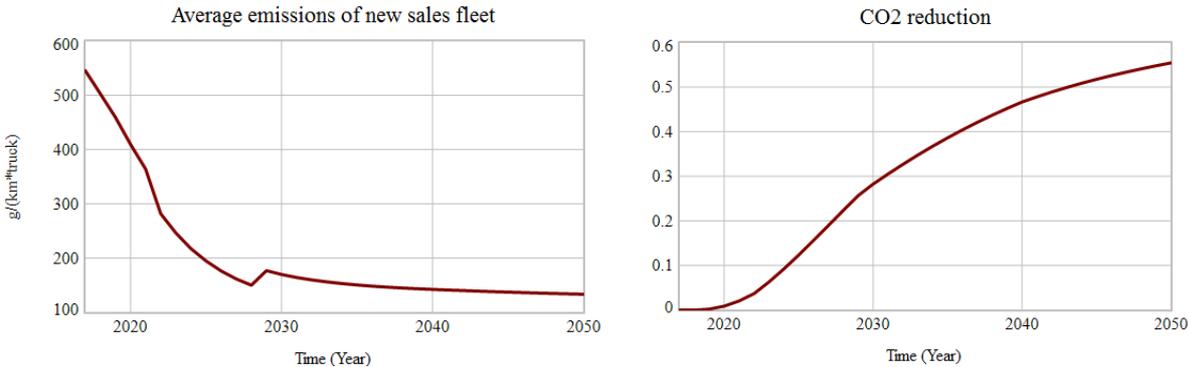


Figure 50 Average CO<sub>2</sub> emissions of new sales fleet and operating profit margin and CO<sub>2</sub> reduction potential in Pro Electric Mobility Scenario

In the Pro-Electric-Mobility Scenario, a Well-to-Wheel greenhouse gas reduction of nearly 55.45 percent is reached relative to a scenario, in which electric trucks are not offered (see Figure 50).

### 5.8 CONTRA ELECTRIC MOBILITY SCENARIO

The scenario is characterized by exactly the opposite of what is assumed for the Pro Electric Mobility Scenario. A low diesel fuel price and a fast implementation of diesel fuel saving measures make diesel trucks very competitive. Contrary to that, the energy consumption reduction rate for electric trucks is lower than in the Baseline Scenario. Furthermore, a high battery cost due to low learning rates and a customer behaviour that is very cost sensitive put electric trucks into a difficult position. Customers also have concerns regarding the electric driving range, and the infrastructure and service station availability. Environmental considerations do not significantly drive the purchase decision. In addition to that, a battery replacement is needed during the service life of the battery electric truck, which results in higher maintenance and repair costs per km. Manufacturers do not have an interest in promoting electric trucks, and the government refuses to give grants to customers who want to buy electric trucks. The government does not support R&D projects of manufacturers which want to improve the efficiency of electric trucks. This results in lower learning rates for batteries and fuel cells. The following Table 25 lists all parameters that are changed in favour of diesel trucks in the Contra Electric Mobility Scenario.

Low diesel fuel price assumption	Diesel fuel price: €1.0681
Fast internal combustion engine efficiency improvements	Low adjustment time for fuel consumption reduction: 5 years
Low learning rates for batteries	0.05
Low learning rates for fuel cells	0.1
Purchase price weight	-0.1
Driving range weight	0.5

Infrastructure and service station availability weight	0.25
CO <sub>2</sub> emissions parameter weight	-0.02
Marketing efforts	0.005
Subsidies for EVs	None
Higher maintenance and repair costs per km due to battery exchange for battery electric trucks	0.08 €/km

Table 25 Parameter values in the Contra Electric Mobility Scenario

The simulation results show the undisputed position of the diesel truck as the dominant transport mode in urban freight transport. Only the plug-in hybrid electric truck can gain market shares. There are no noteworthy sales of battery electric trucks and fuel cell electric trucks (see Figure 51).

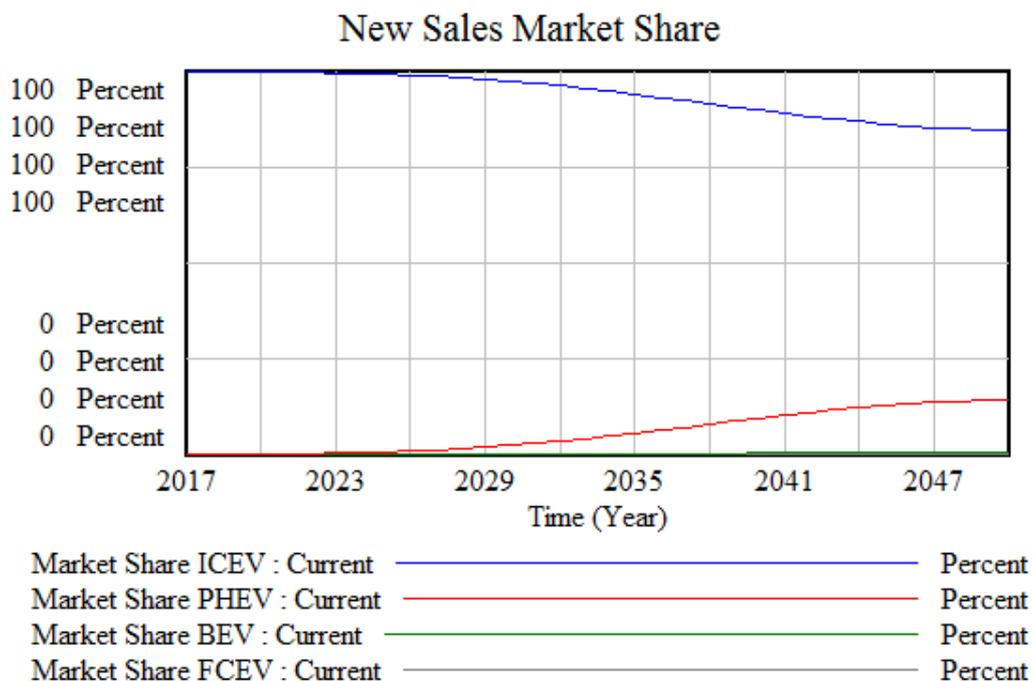


Figure 51 New sales market shares in the Contra Electric Mobility Scenario

There is no remarkable progress in battery technology in terms of cost per kWh battery capacity and energy density. After the increase of the CO<sub>2</sub> emission standard in 2030, the truck manufacturers' CO<sub>2</sub> penalty payments increase sharply leading to a dramatic decrease of the operating profit margin (see Figure 52).

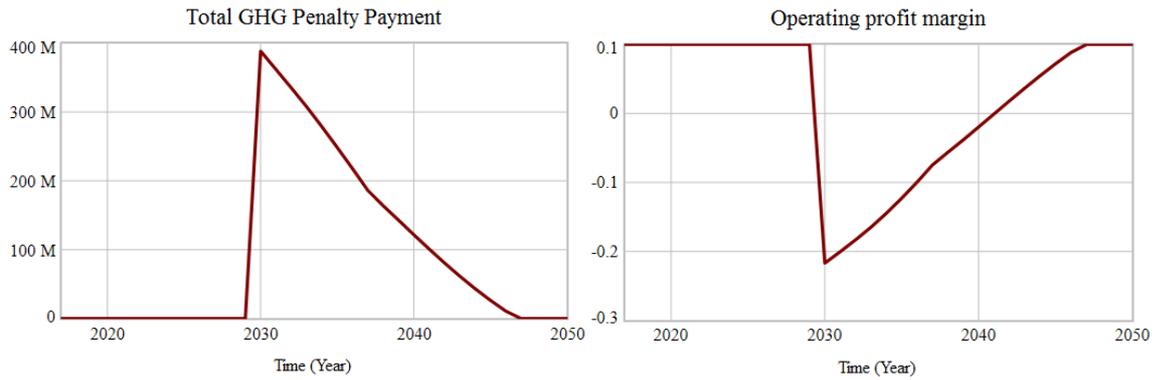


Figure 52 GHG penalty payment and operating profit margin in Contra Electric Mobility Scenario

Truck manufacturers do not achieve the CO<sub>2</sub> emissions limit until 2050. The CO<sub>2</sub> reduction potential is only marginal. It even did not reach one percent. Truck manufacturers collect CO<sub>2</sub> emission credits until 2025 due to efficiency improvements of the diesel drivetrain, which they can then use to comply with the CO<sub>2</sub> emission limit in 2025. Due to an absence of electric truck sales, truck manufacturers generate CO<sub>2</sub> emission debts from 2025 onwards (see Figure 53). The resulting CO<sub>2</sub> penalty payments lead to a deterioration of the operating profit margin of truck manufacturers for a long period.

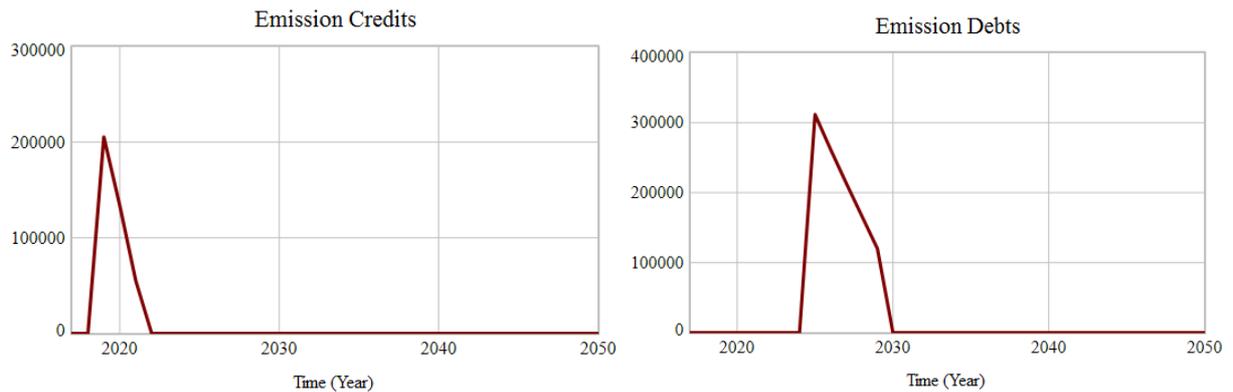


Figure 53 CO<sub>2</sub> emission credits and debts in Contra Electric Mobility Scenario

## 6. CONCLUSIONS AND OUTLOOK FOR FUTURE RESEARCH

It has to be kept in mind, that this model is only a simplified version of the real market conditions and that the results should be interpreted with caution. However, the findings can give stakeholders a sense of which levers need to be activated to achieve a shift from conventional to electrified vehicles in urban freight transport.

The conclusion of the Marketing Scenarios is that marketing efforts and the level of word-of-mouth between truck operators influence the diffusion potential of electric trucks dramatically. Manufacturers should set up trials which prove the fuel saving benefits of electric trucks and reduce the range anxiety of truck operators. Political authorities can set-up web pages and provide truck operators with the latest information on electric truck options, trial results, charging and refuelling infrastructure locations, governmental regulations and subsidies<sup>659</sup> and organize workshops, which bring together different stakeholders of the freight transport market.<sup>660</sup> These measures will stimulate the word-of-mouth for electric trucks and by this lead to higher diffusion rates.

The results of the Energy Price Scenarios reveal that a higher diesel fuel price, which widens the operational cost gap between efficient electric trucks and diesel trucks, can accelerate the sales rates of electric trucks. Higher taxation of diesel fuel can achieve a higher energy price differential between diesel trucks and electric trucks.<sup>661</sup>

Electric trucks need to improve in economic and technical terms to be able to replace the incumbent diesel truck in urban freight transport. The Learning Rate Scenarios demonstrated the importance of battery cost reductions due to economies of scale and R&D investments, which narrowed the purchase price differential between diesel trucks and electric trucks. R&D investments of manufacturers do not only decrease the battery pack costs, but also increase the energy density of batteries. With a fixed battery size, a higher battery energy density enables higher electric driving ranges and thus increases the attractiveness of the electric truck options battery electric truck and plug-in hybrid electric truck. The government can support manufacturers' R&D

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<sup>659</sup> Lyons, S. and Chatterji, P. (2016), p. 24

<sup>660</sup> Ibid.(2016), p. 40

<sup>661</sup> Teter et al. (2017), p. 137

projects, which will bring down the costs of batteries and enhance the technological reliability of electric trucks, with research subventions or loans with lower interest rates<sup>662</sup> or support demonstration projects, which will proof the applicability of electric trucks in urban freight transport and thus increase the confidence of truck operators in the new technology.

The Purchase Subsidy Scenarios have shown that a purchase subsidy is an effective fiscal measure to scale up the diffusion of electric trucks. However, the right timing of purchase subsidies is important as subsidies are more effective when the initial uncertainty of truck operators about the benefits of electric trucks and their suitability to their transport operations is reduced. In addition to purchase subsidies, policymakers should consider grants for electric vehicle charging infrastructure, as charger costs deteriorate the sales rate of electric trucks.

In addition to charging infrastructure subsidies, political authorities should support the construction of a minimum number of hydrogen refuelling stations and rapid battery charging points to circumvent the chicken-egg problem. The provision of a minimum number of public refuelling stations is especially important for the fuel cell electric truck, as it is unlikely that urban freight transport companies will install hydrogen refuelling pumps at their own depots.

The measures above will be accompanied by a challenging fuel economy standard, which will incentivize truck manufacturers to increase the sales rate of electric trucks. But the CO<sub>2</sub> emissions limit and the associated CO<sub>2</sub> penalties should not turn the operating profits of truck manufacturers into negative figures, as otherwise, manufacturers will not have financial resources to invest in clean technologies. On the other hand, a regulatory framework in favour of electric trucks provides manufacturers with the security that R&D investments in electric trucks will pay off.<sup>663</sup> Therefore, it is important to set an appropriate CO<sub>2</sub> emissions limit for 2025 and 2030.

The highest CO<sub>2</sub> reduction potential was achieved in the Pro Electric Mobility Scenario. However, even in this scenario, the CO<sub>2</sub> reduction did not exceed 55 percent. The government needs to encourage the decarbonization of electricity and hydrogen generation to achieve high CO<sub>2</sub> reductions in freight transport.

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<sup>662</sup> den Boer et al. (2013), p. 102

<sup>663</sup> Lyons, S. and Chatterji, P. (2016), p. 20

The dissertation did not include payload capability differences between truck types, as it is assumed that policy makers will extend the 1-tonne weight allowance to rigid trucks used in urban transport.<sup>664</sup> Policymakers should put this on their agenda.

Another factor which has not been included in the utility function is the resale value of trucks. But a significantly lower resale value of electric trucks will discourage truck operators to adopt them. Manufacturers can respond to this challenge by offering buy-back options<sup>665</sup> or innovative leasing models. Besides that, truck manufacturers need to invest in service stations so that they can provide maintenance and repair services for electric trucks.<sup>666</sup>

As one might expect, the customer behaviour exerts a huge influence on the diffusion of electric trucks. Green customer behaviour leads to an increase in sales market shares of electric trucks. It is important to make the green image profitable in order to be able to exploit this potential.<sup>667</sup> For example, companies deploying electric trucks could be awarded sustainability labels, and goods receivers could be informed by information campaigns about transport companies' contributions to environmental protection.<sup>668</sup>

A lack of financial resources for financially restricted companies delays the diffusion of battery electric trucks until the battery electric truck becomes cost-competitive. The cost-competitiveness of battery electric trucks is mainly achieved by a decrease in battery cost due to plug-in hybrid electric truck sales. Banks should, therefore, facilitate the loan application process for small and financially weak transport companies.<sup>669</sup>

The dissertation can be further enriched and expanded methodologically and thematically in different directions.

One thematic expansion could be the inclusion of tractor-trailers and construction and municipality vehicles. This would necessitate the inclusion of the catenary wire or battery swapping technologies for long-haul transport battery electric trucks. As the TCO of a truck is the most important purchase criteria for long-haul transport, it is recommended to use the function NPV in Vensim, which calculates the Net Present

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<sup>664</sup> Lyons, S. and Chatterji, P. (2016), p. 23

<sup>665</sup> Ibid. p. 22

<sup>666</sup> Ibid.

<sup>667</sup> Baster et al. (2014), p. 25

<sup>668</sup> Ibid., p. 36f.

<sup>669</sup> Teter et al. (2017), p. 138

Value. The inclusion of all heavy duty types would also allow modelling the setting of CO<sub>2</sub> standards in greater detail. Another option is to broaden the scope to include all Triad Markets. The latter could include the investigation of spillover effects between different markets on the diffusion of electric trucks.

The dissertation concentrates on electric trucks and has excluded trucks, which use natural gas or biofuels for the propulsion. In addition to that, vehicle categories like the range-extended electric vehicle (REEV) or Diesel Flywheel and Diesel Hydraulic Hybrid vehicles have been excluded. The inclusion of these truck types, however, will give additional insights about the valuation of powertrain options by customers but will lower the market potential and the diffusion rates of the vehicle categories plug-in hybrid electric truck, battery electric truck and fuel cell electric truck. In this context, the model of Matějka and McKay could be compared with a Nested-Logit-Model, as the natural gas, biofuel, Diesel Flywheel and Diesel Hydraulic hybrid trucks share more characteristics with the diesel truck than with electric trucks. Consequently, building two nests with diesel, natural gas, biofuel, diesel flywheel and diesel hydraulic hybrid trucks within one nest and electric trucks within the other nest, could deliver more precise results.

The dissertation uses parameter weights from a car study, which have been adapted to simulate truck customer behaviour. Nevertheless, a survey of truck customers would deliver correct parameter weights. In this context, the maximum willingness to pay more of truck customers and the effect of fleet size on purchase probability of electric trucks could be inquired.

The dissertation regarded the manufacturers as one entity. However, a distinction could be made between an incumbent manufacturer and a new market entrant that only offers battery electric trucks. The goal of this investigation would be to analyse whether a First Mover Strategy and a Get Big Fast strategy by cutting prices are the right strategies to gain higher market shares than the competitor.<sup>670</sup>

Based on the inclusion of a competitor into the model, the implementation of zero-emission vehicle mandates that require the manufacturer to sell a minimum percentage of zero-emission vehicles per year becomes possible. Manufacturers that exceed the targets would earn credits, which can be sold to other manufacturers. This

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<sup>670</sup> Sterman et al. (2007), p. 1

credit trading, which is already applied for medium-duty vehicles in California<sup>671</sup>, thus enables manufacturers to close their zero-emission vehicle sales gap.<sup>672</sup>

Another fruitful research question is the impact of electric car and van diffusion on the diffusion rates of commercial vehicles. Tesla announced that it would enter the electric truck market and will thereby build on its experience with passenger cars.

The effectiveness of financial measures like a scrappage scheme with regard to the diffusion rates of electric trucks and the reduction of total greenhouse gas emissions output of freight transport could be tested. The British Government announced in its plan for tackling roadside nitrogen dioxide concentrations that it will consult over the possibility of introducing a scrappage scheme for cars and vans.<sup>673</sup> A scrappage scheme is a financial measure that can be used to spur the sales of more efficient vehicles by removing old and pollutant vehicles off the road. Governments could use two types of scrappage bonuses, namely Cash-for-Scrappage and Cash-for-Replacement.<sup>674</sup> The prime objective of the Cash-for-Scrappage strategy is to get rid of the old and fuel-inefficient vehicles, why it does not dictate with which type of vehicle it has to be replaced.<sup>675</sup> The Cash-for-Replacement strategy defines conditions for the bonus.<sup>676</sup> These two scrappage types could be tested regarding their effectiveness in spurring the sales rates of electric trucks.

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<sup>671</sup> California Environmental Protection Agency, p. 6

<sup>672</sup> Teter et al. (2017), p. 134

<sup>673</sup> Defra (2017b), p. 10

<sup>674</sup> Brand et al. (2013), p. 135

<sup>675</sup> Ibid.

<sup>676</sup> Ibid.

## 7. SUMMARY

Today, we are on the cusp of a new revolution in freight transport. Truck manufacturers are pressing forward into the urban freight market with new electric trucks and praise them as the solution to the noise and air pollution problems with which cities are faced. The supremacy of diesel trucks in freight transport is not only threatened by technological and economic enhancements in the development of electric trucks, but also by regulations of governmental authorities, which are introducing Low or Zero Emission Zones with a time-restricted or complete ban on high-emission vehicles or by charging a fee depending on the level of greenhouse gas and exhaust emissions of the truck. In light of global warming, the European Commission is preparing the introduction of the European CO<sub>2</sub> emission standard for commercial vehicles. In its Transport White Paper, the European Commission has set a long-term objective of overall EU transport greenhouse gas emissions reductions of about 60 percent in 2050 compared to 1990. Furthermore, it is envisioned to make city logistics in major urban centres CO<sub>2</sub> free by 2030, what will trigger a shift towards electric trucks from 2020 onwards. The dissertation intends to analyse how this shift to electric freight transport will happen and which factors will foster and which will hinder the diffusion of electric trucks in urban freight transport. The focus of the dissertation is on urban delivery, as it is believed to be the ideal seedbed for the electrification of freight transport. Electric delivery trucks fit perfectly with the hub-and-spoke concept, which is gaining importance in urban freight transport. In this concept, goods are transported with large tractor-trailers to logistic hubs on the outskirts, where they are transferred to lighter trucks, which then bring the goods to their destinations. Electric trucks are ideally suited for last-mile delivery tasks in cities, as the shorter driving distances do not limit the application potentials of electric trucks. Furthermore, electric trucks normally can drive into Zero Emission Zones without having to pay any charge. In addition to that, transport companies in urban freight transport are the main target group for electric truck manufacturers, as trucks used by these transport companies have high visibility to consumers. Companies can use green trucks to show their environmental responsibility and to build up a green image.

There are different stakeholders in the trucking business like truck manufacturers, transport companies, fuel suppliers and governmental authorities, which have

particular interests and take decisions based on these interests. The trucking industry is inherently very complex. System Dynamics is a tool that has been developed to understand such dynamic and complex relationships between market actors. The diffusion model is implemented as a System Dynamics model, which incorporates the feedback mechanisms like the development of battery cost depending on sales rates of electric trucks. After having described the relationships between the urban freight market actors in a System Dynamics Model, scenario planning has been used to assess the impact of different model variables on the diffusion of electric trucks and to understand, which policy strategies have the potential to boost the sales rate of electric trucks.

The simulation result of the Baseline Scenario has shown that the plug-in hybrid electric truck is the most promising drivetrain technology for urban freight transport. However, the battery electric truck can increase its market shares with increasing battery production experience and decreasing battery cost. The fuel cell electric truck stays a niche technology until 2050. Despite all enhancements regarding battery technology and costs, the diesel truck is still the truck type with the highest sales market share in 2050.

The scenarios demonstrated that the uptake of electric trucks could be supported with different measures. It has been shown that measures like electric truck purchase subsidies and diesel fuel taxes, which reduce the purchase price and operating cost differential between diesel and electric trucks, are very effective. Almost equally important for the diffusion of electric trucks, however, are marketing efforts and word-of-mouth propaganda, which reduce the uncertainty about the benefits and the operational suitability of electric trucks and thus helps to make rational inattentive truck customers to make better purchase decisions and to battle the energy efficiency paradox in freight transport.

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