Exploring the effects of carbon pricing on the decarbonization of freight transportation in the Netherlands

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Exploring the effects of carbon pricing on the decarbonization of freight transportation in the Netherlands

by

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PREFACE

This report is the final result of my thesis for the master programme Transport, Infrastructure and Logistics at the TU Delft. I performed a study at Panteia in which I researched two fields that I am very interested in: the transportation sector and sustainability.

I would like to thank my supervisors for the support during the study. Bart, thank you for the critical yet constructive remarks on my study. Thanks to Tharsis for always being open to my questions and for the brainstorm sessions on the research. I would like to thank Laurens for giving me new insights about the energy sector, on which I have learned a lot during my project. Furthermore, thanks to Lóri for linking me with the company and the feedback during the meetings.

Finally, I would like to thank my parents and friends for supporting me during the study. Thanks for the discussions about the project and for making the remaining spare-time very enjoyable.

I hope you enjoy your reading.

Maaike de Vries
Zoetermeer, October 2019

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SUMMARY

In 2015, the UN climate agreement was signed by the Netherlands, which has the central aim to "strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius" (UNFCCC, 2018). To be able to achieve this, "a reduction of at least 60% of GHGs by 2050 with respect to 1990 is required from the transport sector" (EC, 2011).

This research focuses on three methods that were identified by Kaack et al. (2018) for the reduction of emissions in the transport sector: increasing the efficiency of freight vehicles, reducing the carbon content of fuel used to transport freight and shifting freight to low carbon-intensity modes. To be able to stimulate the freight transportation sector to the three alternatives, a pricing policy that includes the CO_2 emissions of the modes is identified: carbon pricing (Beuthe et al., 2002).

Current literature has studied the influence of a carbon price on the container freight transport in the Netherlands while focusing on the modal shift (Zhang et al, 2014; Zhang et al, 2015) or researched the effects of internalizing the external costs on the Belgium freight transportation network (Beuthe et al, 2002). Furthermore, the influence of a carbon price on the potential for urban freight electrification in Madrid was researched by Arroyo et al. (2019).

This research contributes to clarifying the effects of carbon pricing on the Dutch freight transportation. As current studies mainly focus on either the effects on the modal shift or the effects on the use of alternative fuels, these do not consider a combination of the effects and do not take into account the increase in the efficiency of the freight vehicles. Furthermore, the current literature focuses on a particular niche market (e.g. only container or a certain region). This research takes a broader view and looks at the influence of the carbon price on all commodities that have an origin, destination or both in the Netherlands. The main research question of this research is:

HOW CAN THE FREIGHT TRANSPORTATION NETWORK USE IN THE NETHERLANDS BECOME MORE SUSTAINABLE, CONSIDERING MODAL SHIFT AND ALTERNATIVE FUELS?

Currently, most freight is transported by trucks, which is a more expensive mode but has a high network density and enables faster transportation as there is no need for transhipment between modes (Platz, 2009). Inland waterway (IWW) is the second most used mode for freight transportation in the Netherlands (CBS, 2019_b). IWW is a cheaper mode, but the transport is dependent on the available ports in the waterways network and is a slow mode of transportation. Rail freight transportation is used the least in the Netherlands (KiM, 2016). The rail mode can be cheap, however transhipment is expensive. Next to that, the trains are dependent on the railways service stations and do not reach high speeds due to inefficiencies (Islam & Zunder, 2018; Janic, 2008).

When looking at the emissions of the modes, a clear difference between the emissions is identified: trucks emit up to 2.5 and 5 times more CO_2 than IWW and rail respectively (KiM, 2016). This results in an unsustainable distribution: the mode that emits the most emissions is used the most while the most sustainable mode is used the least.

To be able to explore the effects of carbon pricing on the freight transportation system, an analysis on how the carbon price might stimulate the reduction of the CO_2 emissions is performed. The influence of the carbon price on three areas is analysed: the influence on the energy generation market, the influence on the choice of fuel and the influence on the choice of the transport mode. The influence on the energy generation market refers to the influence of the carbon price on the improvements of conventional diesel vehicle technology. This results in a decrease of the emissions when the carbon price increases. A linear decrease of the emissions is assumed, in which the IWW mode decreases the most, followed by road and rail respectively. Next to that, the influence on the electricity generation market is explored. The fuelswitch-effect results in an increase in the share of renewable energy, resulting in a decrease in emissions for the use of electricity.

The second area, the influence of the carbon price on the fuel choice, is caused by the increasing price of unsustainable fuels while the price of more sustainable fuels increases less. Therefore, transport planners might choose a more sustainable fuel type. This study focuses on battery electric vehicles (BEVs) and hydrogen fuel cell vehicles (HFCVs). To analyse this influence, a vehicle choice mode based an all-or-nothing (AON) algorithm is used. This algorithm assumes that all transport planners make the same decision which in this case is solely based on cost minimization.

The third area which the carbon price might influence is the choice of transport mode. The transport operation will become more expensive due to the price, with the less sustainable modes getting more expensive than the more sustainable modes. Therefore, transport planners may switch to more sustainable modes. To be able to simulate this, a freight transportation model is used that makes use of discrete choice modelling. This type of modelling results in a probability to choose a certain alternative.

To be able to determine the influence that a carbon price has on the use of alternative fuels, the Panteia TCO (total cost of ownership) model is used. The Panteia TCO model was made for the comparison of the TCO of BEVs and diesel vehicles for several vehicle types. The model calculates the total cost of ownership by adding up different types of costs. By adding the carbon price per vehicle to the TCO model and changing the input of the mileage per year, the mileage per year where electricity is cheaper than diesel per carbon price level is found.

As a freight transportation model, the BasGoed model is used. The BasGoed model estimates the production and consumption of zones within Europe and the associated transportation flows per mode. The distribution and modal split modules are used for the production and consumption of the zones and the resulting flows per mode. To determine the modal split, the BasGoed model takes into account the costs, the time, the containerization, whether a border is crossed and constants that refer to the preference of taking a certain mode per origin, destination and mode (Rijkswaterstaat, 2018). The BasGoed model uses six scenarios, called the WLO (Welvaart en Leefomgeving) scenarios (Significance, 2015). The scenarios are a ‘high’ and ‘low’ possibility for the years 2030, 2040 and 2050. The difference between the high and low scenarios is created by expected differences in economic factors, international policy, logistics development and national policy.

BasGoed currently has included emissions cost for IWW in the high scenarios as it was assumed that the IWW sector is involved in the EU emissions trading system from 2030 and on. However, other emissions are not included in the BasGoed model. Therefore, some adjustment are made to perform the analysis. First of all, the results of the Panteia TCO model are used as a range where electricity is used as fuel in the

BasGoed model. To be able to link the yearly mileages of the TCO model to the distances in the BasGoed model, assumptions are made. This results in a distance range where trucks switch to electricity as fuel per carbon price level. It is assumed that 100% switches to electricity as fuel within the resulting distance range. Next to the introduction of the BEVs, the carbon price is added to the distance related cost in BasGoed by finding an average amount of CO_2 emissions per vehicle per mode.

The result from the TCO model shows that from a price of €330/ton CO_2 battery electric vehicles become cheaper in certain distance ranges. The maximum range of BEVs is 150 km and the larger ranges become cheaper first. At a price of €500/ton CO_2 the maximum range that is found is 80-150km. When this is, together with the carbon price, implemented into the modal split module of BasGoed, the modal split in tonnes does not show changes. However, when looking at the modal shift per distance class, a shift in tonnes at large distances is shown. Next to that, when BEVs are introduced as a cheaper alternative, a reverse modal shift towards the road mode occurs.

When the modal split in ton kilometres (tkm) is researched, a decrease in the share of road freight transportation can be identified. Most of the freight is shifting towards IWW, followed by rail. However, when BEVs are introduced, the shift away from road transportation decreases.

The amount of CO_2 emissions decreases gradually when the carbon price is introduced, until the point where the carbon price enables the BEVs to become economically viable. The introduction of the BEVs results in an accelerated decrease of the emissions. However, the introduction of the CO_2 price results in an increase of the total system cost. Even though the costs of the transportation performance decrease due to the shift to cheaper modes (e.g. IWW and rail), this cannot compensate for the total increase in the cost due to the carbon price.

It can be concluded that introducing a CO_2 price is an effective policy for the reduction of CO_2 emissions in the Netherlands. The effect that has the most influence on the reduction in emissions is the improvement of the technologies for the conventional diesel vehicles and the fuelswitch-effect. Next to that, a slight modal shift to more sustainable modes takes place. Furthermore, when the carbon price makes BEVs an economically viable option, this results in a reverse modal shift; using the road becomes cheaper and more attractive. As BEVs have few emissions, this leads to an accelerated decrease of the CO_2 emissions.

However, it should be taken into account that the introduction of a CO_2 price leads to an increase in the total system cost. This increase is only due to the carbon price and not due to the costs of the transportation itself. The impact of the increase in the total system cost is not taken into account in this study, but can result in major changes in the economy.

It is important to mention that these results should not be interpreted as what would happen in the future. Rather, the results of this study give an idea of what the effects of carbon pricing could be and how this is related to the CO_2 emissions of the freight transportation in the Netherlands. Above all, this research focuses on the increase of the vehicle efficiency, the changing modal split and use of alternative fuels without taking into account any other possible changes caused by a carbon price. However, the carbon price can influence many other fields. For example extra infrastructure investments might be done and changes in the economy might occur. These fields could in their turn influence the results of the study.

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List of Abbreviations

AFV:	Alternative fuels vehicle
AON:	All-or-nothing
BasGoed:	Basismodel Goederenvervoer
BEV:	Battery Electric Vehicle
BIVAS:	Binnenvaart analyse systeem
COROP:	Coördinatie commissie Regionaal OnderzoeksProgramma
CO_2:	Carbon dioxide
ETS:	Emissions trading system
GHG:	Greenhouse gas
Gvw:	Gross vehicle weight
H2030:	The high 2030 scenario
H2050:	The high 2050 scenario
HFCV:	Hydrogen Fuel Cell Vehicle
IWW:	Inland waterway
Km:	Kilometres
L2030:	The low 2030 scenario
L2050:	The low 2050 scenario
LMS:	Landelijk Model Systeem
MoT:	Ministry of transport
NO_x:	Mono-nitrogen oxides
NSTR:	Nomenclature uniforme des marchandises pour les Statistiques de Transport, Revisée
NUTS:	Nomenclature of territorial units for statistics
OD:	Origin-Destination
TCO:	Total cost of ownership
Tkm:	Ton kilometres
TTW:	Tank-to-wheel
VKM:	Vergelijkingskader modaliteiten
WLO:	Welvaart en leefomgeving: Welfare and environment
WTW:	Well-to-wheel

1 INTRODUCTION

1.1 BACKGROUND

Climate change has been an important topic of discussion for the last couple of years. As greenhouse gas (GHG) emissions amplify the global warming, a reduction of emissions is needed. Therefore, policy makers have introduced guidelines and laws to be able to make that happen. In 2015, the UN climate agreement was signed by the Netherlands, which has the central aim to "strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius" (UNFCCC, 2018). To be able to achieve this, "a reduction of at least 60% of GHGs by 2050 with respect to 1990 is required from the transport sector" (EC, 2011).

As passenger and freight transportation globally contributes 23% of energy related carbon dioxide (CO_2) emissions (IEA, 2017) and the numbers of transportation are expected to increase with 8% to 10% in the Netherlands between 2018 and 2023 (KiM, 2018), the transport sector is important to be able to decrease global energy emissions. However, instead of a decrease, the CO_2 emissions of traffic and transport in the Netherlands have increased by 30% between 1990 and 2004, which is mainly due to an increase of the amount of traffic as the CO_2 per kilometre has decreased (CBS, 2018_a).

Therefore, it seems that even though the high importance of reducing the emissions in the transport sector, it is a challenge to make it happen. To be able to realize the decrease, Kaack et al. (2018) identified five possible methods to decarbonize freight transport:

1. Reducing the demand for freight transport
2. Optimizing vehicle use and loading
3. Increasing the efficiency of freight vehicles
4. Reducing the carbon content of fuel used to transport freight
5. Shifting freight to low carbon-intensity modes

The first two alternatives are dependent on logistics management. The third, fourth and fifth alternative can be strongly influenced by government policy. Therefore, these three alternatives will be elaborated.

1.1.1 Increasing the efficiency of freight vehicles

Vehicle fuel efficiency has a major influence on the vehicle emissions (Taptich et al., 2015). The efficiency of the freight vehicles can be increased by technological improvements. For trucks, ICCT (2017) states that by for example improving engine efficiency and aerodynamics, improvements in heavy-duty vehicles efficiency and emissions can be obtained. For the rail mode, the efficiency can be increased by for example the line layouts and the rolling stock (International union of Railways, 2016) while for transportation over water there is a potential for savings due to, for example, hydrodynamic measures and the optimisation of the ships speed (CCNR, 2012).

Even though the high potential of the energy savings, some barriers are identified regarding the adoption of the new technologies. The new technologies can be expensive and there is an uncertainty in exploring the new technologies (Kaack et al, 2018).

1.1.2 Reducing the carbon content of fuel used to transport freight

Reducing the carbon content of the fuel can directly reduce the CO_2 emissions of transport. Currently freight vehicles depend on predominantly diesel, which is responsible for the increase of the CO_2 in the atmosphere (Singh et al., 2015). Possible alternative fuels are Biodiesel, Electricity, Ethanol, Hydrogen, Methanol, Natural Gas, LPG, Solar energy and P-series fuel (Johnston et al., 2005). By introducing new technologies and new fuels, the emissions by freight transportation modes could decrease. García-Olivares et al. (2018) state that by introducing a 100% renewable transport system that serves the demand of the world transport in 2014, a decrease of 18% in energy would be met. Next to that, Nocera & Cavallaro (2016) state that 'non-fossil fuels can reduce carbon emissions noticeably'.

Even though alternative fuels are generally better for the environment (e.g. less emissions and quieter vehicles) and only little has to be adjusted, vehicles using alternative fuels are expensive and the supply of the alternative fuels is uncertain as it is a relatively new technology (McKinnon et al., 2010).

1.1.3 Shifting freight to low carbon-intensity modes

Another possibility to decarbonize freight transport is to shift the freight to low carbon-intensity modes. To be able to do so, the European Commission has tried to promote a shift from road freight transport to other more sustainable modes as the average carbon intensity of intermodal transport is 46% lower than truckload (Craig et al., 2013). However, Kaack et al. (2018) state that most countries are experiencing a shift from rail to road. Jonkeren et al. (2019) conclude that a modal shift from road (-3.0 percentage points (p.p.)) to rail (+0.2% p.p.) and inland waterways (+2.8 p.p.) has occurred between the years 2005-2014 in the Netherlands. This shift occurred only in the freight distance market for more than 100 km. This means only a little has changed in the past couple of years.

One of the reasons little has changed is because "the rising share of higher value commodities and the associated need for fast and on-time deliveries have continued to gradually shift the relative importance away from waterways and railways toward trucks and aircraft" (Gucwa & Schäfer, 2013). This results in an increase in the average energy intensity of the freight transportation system. Next to that, "it is often difficult for policy makers to assess how rail and inland waterways can attract cargo" (Jonkeren et al., 2019).

1.1.4 Carbon pricing

One way to promote the three methods that can decarbonize transport is to introduce a price for the CO_2 emissions. By including the external effects of each mode, the transportation modes that emit less CO_2 can be promoted (Beuthe et al, 2002): by increasing the prices according to the amount of CO_2 emissions, an economic motive to switch to other modes might arise. Next to the promotion of other transport modes, carbon pricing can also influence the decision to use alternative fuels as this might become a cheaper option. Furthermore, when transport planners must pay for the emissions, investing in new technologies that enable transportation with less emissions becomes attractive.

1.2 Research problem

As transport planners focus on time and cost for their freight transport routes, the sustainability of the freight transportation network is set back. Sustainable possibilities are already offered but only few are used. When looking at the Dutch transport routes network, different modes might be chosen when the focus is on the emissions of the routes instead of time or cost. For example, when transporting freight from the port of Rotterdam to a distribution centre in Arnhem, it is possible to move the freight by truck, by rail or by barge. The fastest way of transportation is by using a truck. However, the truck might not be the most sustainable way of transportation. Next to that, alternative fuels might also influence the decisions on which modes are used in the freight transportation network.

Several studies have researched the introduction of a carbon price to the freight transportation system. Zhang et al. (2014) and Zhang et al. (2015) researched the effects of the price on container transportation in the (hinterland of the) Netherlands, where the main focus was on the effect on the modal split. Beuthe et al. (2002) researched the effects of internalizing the external costs on the Belgium freight transportation network, focusing on the modal shift. Arroyo et al. (2019) researched the influence of the carbon price on the potential for urban freight electrification in Madrid.

This research contributes to clarifying the effects of carbon pricing on the Dutch freight transportation. As current studies mainly focus on either the effects on the modal shift or the effects on the use of alternative fuels, these do not consider a combination of the effects and do not take into account the increase in the efficiency of the freight vehicles. Furthermore, the current literature focuses on a particular niche market (e.g. only container or a certain region). This research takes a broader view and looks at the influence of the carbon price on all commodities that have an origin, destination or both in the Netherlands.

1.3 Objective

This research's main objective is to find what the effects of carbon pricing are on the freight transport in the Netherlands when considering the emissions, modal shift and the sources of energy. Several sub objectives can be distinguished:

- To research the influence of carbon pricing on the alternative energy sources for freight transportation in the Netherlands.

- To research the influence of carbon pricing on the shift to low-carbon intensity modes in the given Dutch transportation network.
- To research the possible reduction of emissions caused by the change of fuels and the change to low-carbon intensity modes.

1.4 Research question

To be able to achieve the objective, a main research question was found:

HOW CAN THE FREIGHT TRANSPORTATION NETWORK USE IN THE NETHERLANDS BECOME MORE SUSTAINABLE, CONSIDERING MODAL SHIFT AND ALTERNATIVE FUELS?

To be able to find an answer to the main question, several sub questions are identified:

RQ. 1. Which transport modes are currently used and what are the current emissions?

RQ. 2. What shift to alternative fuels can be realized within the Netherlands when looking at the road freight transportation?

RQ. 3. What modal shift can be realized within the Netherlands when looking at the intermodal transport network?

RQ. 4. How can carbon pricing affect the CO_2 emissions of freight transport in the Netherlands, given the transportation modes and energy sources?

1.5 Scope

This study focuses on the effect of carbon pricing on the freight transportation in the Netherlands, considering the current available intermodal network. The freight coming from, going to and within the Netherlands using the following modes are considered:

- Road
- Inland waterway (IWW)
- Rail

The study focuses on the CO_2 emissions of the transportation using these modes. Next to that, the possibility of using the alternative fuels electricity and hydrogen are researched.

1.6 Reading guide

The research starts with an overview of the freight transportation system in the Netherlands in chapter 2, where the characteristics of the modes are explained and the current flows and emissions are illustrated. Chapter 3 elaborates on the structure of the analysis that is performed and explains the scenarios. Subsequently, the used models are explained in chapter 4. Next to the current structure of the models, the introduction of alternative fuels and emissions to the models is explained. Chapter 5 gives the results of the analysis. Finally, chapter 6 reflects on the methodology and results and gives the conclusions and recommendations for further research.

2 FREIGHT TRANSPORTATION IN THE NETHERLANDS: FLOWS AND EMISSIONS

In this chapter the current freight transportation system in the Netherlands is explained. First, an introduction to freight transportation in the Netherlands is given. Chapter 2.2 gives an elaboration of the current situation of unimodal transport in the Netherlands which is followed by an introduction to multimodal transportation in chapter 2.3. Chapter 2.4 introduces the current emissions caused by freight transportation in the Netherlands. The last chapter summarizes the current freight transportation system in the Netherlands.

2.1 INTRODUCTION TO FREIGHT TRANSPORTATION

Several modes can be used to transport freight from an origin to a destination. This research focuses on three modes: road, rail and inland waterway. When only one mode is used to transport the freight, the transportation is called unimodal. When the freight is transported by a sequence of at least two different modes of transportation, the transportation is called multimodal (UNECE, 2009). Each mode has its characteristics, which makes the mode suitable for a certain type of goods or certain type of transport. Therefore, the mode characteristics are important decisive factors for the modal split. Table 2.1 shows an overview of the different characteristics for the modes road, rail and inland waterway, in which a "+" represents a relatively good performance, "0" a medium performance and "-" a relatively poor performance compared to the other modes.

Characteristic	Road	Rail	IWW
Transport costs per unit	-	+	+
Ability to achieve the transport of large volumes	-	+	+
Transport speed	+	0	-
Network connectivity	+	0	-
Predictability of transport processes	0	0	-
Transport frequency	0	0	0
Transport Safety	-	+	+
Transport Security	-	0	+
Convenience and Flexibility	+	-	-
Resistance to extreme weather condition	-	0	-
Limitation of infrastructure capacity, congestion	-	0	+
Energy use per ton-km	-	0	+
Emission of harmful substances	-	+	0
Emission of greenhouse gas	-	+	+
Noise, negative effects on ground and water	-	-	+

Table 2.1: Strengths and weaknesses of land transport modes (Platz, 2009)

The characteristics of the modes result in a consideration for transport planners which mode to use for the freight that has to be transported. The importance of the characteristics of modes differs for transport planners. According to Kopytov & Abramov (2012) the choice of transportation route depends on costs, time, reliability and ecological aspects. Bask & Rajahonka (2017) summarized the selection criteria in several papers and found that costs are the most important according to literature. Next to that, reliability, time and flexibility are frequently mentioned factors. Sustainability is also mentioned several times, but scores the lowest when looking at the total score.

For the mapping and forecasting of freight transportation flows, several classifications are used. Two important classifications are the distinctions of commodities and the geographical classification. A common grouping for commodity types is the NSTR 1-digit level. Table 2.2 shows the meaning of the NSTR levels.

For the geographical classifications, there are several possibilities. The NUTS (Nomenclature of territorial units for statistics classification) is used in Europe for the purpose of collecting statistics, socio-economic analyses and regional policies. It has 3 levels: NUTS1, NUTS2 and NUTS3 in which the last one is the most detailed (EC, n.d.$_a$). In the Netherlands, the COROP (Coördinatie commissie Regionaal OnderzoeksProgramma) zone index is used which corresponds to the NUTS-3 regions that is used in Europe (PBL, 2017). Figure 2.1 shows the COROP zones in the Netherlands.

NSTR level	Meaning
NSTR0	Agriculture
NSTR1	Foodstuffs
NSTR2	Mining
NSTR3	Oil
NSTR4	Ores
NSTR5	Basic metals
NSTR6	Construction
NSTR7	Fertilizers
NSTR8	Chemicals
NSTR9	Miscellaneous

Table 2.2: NSTR-level1 classification (de Jong et al., 2011)

Figure 2.1: COROP zones in the Netherlands (Wikipedia.org, n.d.)

2.2 UNIMODAL FREIGHT TRANSPORTATION: CHARACTERISTICS AND FLOWS

As introduced in chapter 2.1, unimodal transport refers to when only one mode is used for the transportation of the freight. This means no transhipment of goods between different modes is needed in the transportation process. This research focuses on one mode that processes unimodal freight transport: the road. As it was found that costs, time, reliability and flexibility are important to transport planners, these factors are explained here. The reliability and flexibility of the mode are explained using the network characteristics of the transport mode. Next to that, the current flows over the road are elaborated.

2.2.1 Characteristics of road freight transportation

Road freight transportation is transportation by using trucks. It is the most used mode for freight transport in the Netherlands.

Costs

Road freight transportation is more expensive than rail and IWW (Platz, 2009). A part of this can be explained by the fact that road freight transport has a small load capacity meaning the costs cannot be shared by a lot of goods. The costs for road freight transport are dependent on the cost of the driver. When long distances are travelled and sleeping/resting is needed, the costs can rise.

Network

Road freight transportation uses the available road network. The main road network in the Netherlands is shown in Appendix A, Figure A.1. The road network has a high density and therefore the connectivity of road transportation is good. This enables door-to-door transportation making it possible to transport the goods without transhipment between different modes. However, as the truck shares the road network with many other users, road transport is sensitive to congestion. Next to that, road traffic is the mode that experiences the most accidents, decreasing the reliability of the transport (Platz, 2009).

Speed

Enabling transportation without transhipment also results in faster transportation. In the Netherlands, the maximum speed on a highway for trucks above 3.5t gvw (gross vehicle weight) is 80 km/h (freightlink, n.d.).

2.2.2 Road freight flows

Road freight transportation is mostly used for domestic transport. Next to transporting the full distance by a vehicle over the road, road transport is also used for transporting the goods to and from rail and IWW service stations. The left side of Figure 2.2 shows the geographical distribution of loading and unloading goods that are transported by road transportation in 2015. The figure shows that the province of South Holland transports the most tons over the road, followed by Noord Brabant and Flevoland. The right side of the figure shows the share of each NSTR group of road transport in 2017. NSTR group 9 (miscellaneous) has the largest share of the road transportation, followed by NSTR group 6 (construction) and 1 (foodstuffs) respectively.

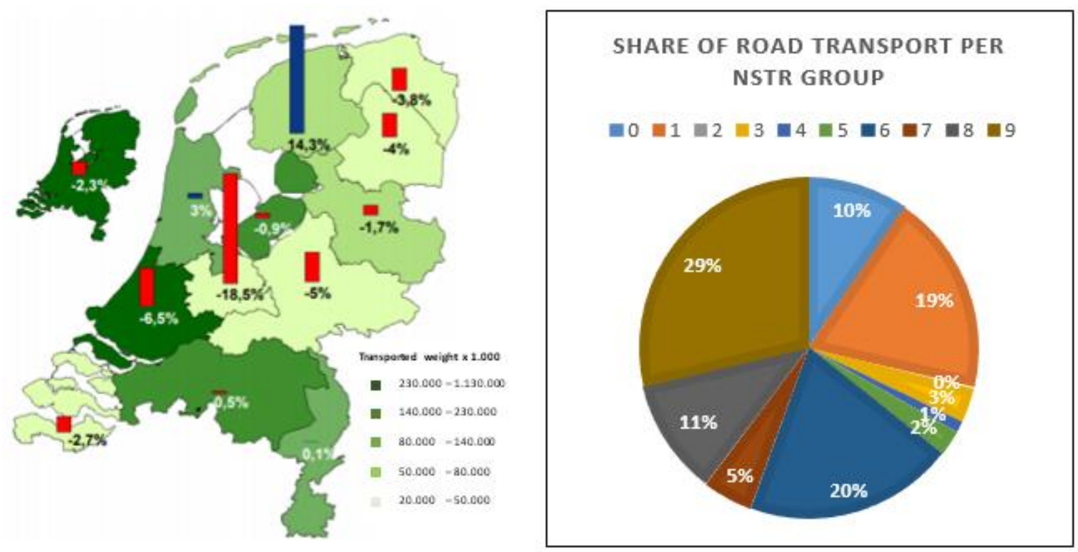

Figure 2.2: Left: Volume loading/unloading from Dutch and foreign transporters per province for road transportation (x 1.000 ton) in 2015, including change from 2010-2015 (Buck consultants international, 2016; CBS, 2016). Right: Share of road transport per NSTR group in 2017 (CBS, 2019a)

2.3 Multimodal freight transportation: Characteristics and flows

Multimodal transportation refers to using more than one mode for the transportation of the freight. This means transhipment between modes is needed. Figure 2.3 shows the processes of multimodal transportation; the freight is brought to the terminal by trucks, where transhipment takes place. When the freight has been transferred, the freight is transported by rail or IWW to the destination terminal where transhipment is carried out. The freight is then brought to its destination by trucks.

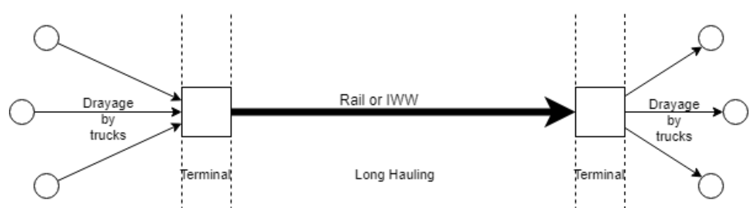

Figure 2.3: The processes of multimodal transportation (Authors figure)

This research focuses on two multimodal transportation modes: inland waterway and rail. The characteristics and current flows of these modes are explained here.

2.3.1 Characteristics of inland waterway freight transportation

Inland waterway transportation makes use of barges to transfer goods. It is the second most used mode for freight transport in the Netherlands (CBS, 2019_b).

Costs

The transport costs of inland shipping are lower than using the road (Platz, 2009). However, the disadvantage of IWW is that often road transportation is needed to transport the freight to/from the origin and destination to/from the barge. This means transhipment is also needed which can reach high prices.

Network

To transport freight over inland waterways, several ships can be used. These ships are dependent on the inland waterways network and the ports that are available. Appendix B shows the Dutch waterways network and their ports. Not all waterways are available for all ships as a certain breadth and depth can be needed for certain vessels. Congestion rarely occurs on the IWW network.

Speed

Inland waterway freight transport is a slow mode for transportation. The maximum speed on canals and rivers is low (20 km/h, sometimes a faster speed is allowed). Next to that, the waterways network contains a lot of bridges and locks which can delay the transportation.

2.3.1.1 Inland waterway freight flows

Most of the IWW freight has an international origin or destination. However, domestic IWW transport also has a share of 36%. The left part of Figure 2.4 shows that the province of South Hollands is the most important for IWW transportation, which can be explained logically because the port of Rotterdam is located there. Considering the NSTR groups, Figure 2.4 shows that NSTR group 4 (ores) has the largest share of the IWW, followed by NSTR 3 (oil) and NSTR 9 (miscellaneous).

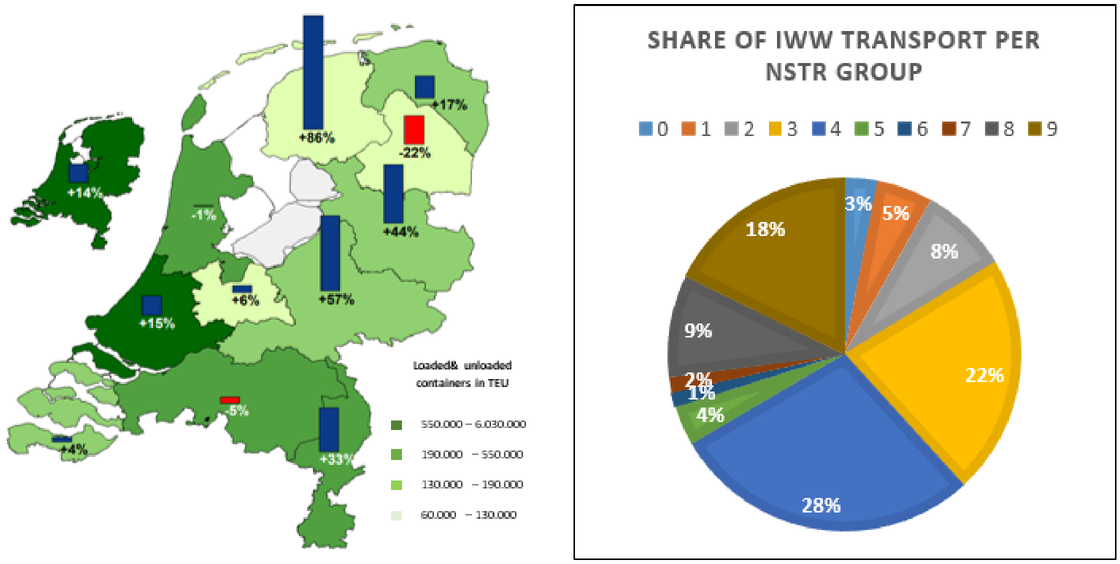

Figure 2.4: Left: TEU loading/unloading per province in 2014, including change from 2011-2014 (Buck consultants international, 2016). Right: Share of IWW transport per NSTR group in 2017 (CBS, 2019c)

2.3.2 Characteristics of rail freight transportation

Rail freight transportation uses trains for the transportation of goods. This mode is not used often in the Netherlands (KiM, 2016). However, when looking at Europe, the train is more popular.

Costs

Rail freight transport itself can be cheap as the capacity of trains can be large while little personnel is needed and little amount of fuel is needed. However, transferring the goods is expensive which means the mode is not beneficial for smaller distances (Islam & Zunder, 2018).

Network

The railway network in the Netherlands is shown in Appendix C. To be able to use the railway network, the freight has to be transported to an available service station. This dependence on the station reduces the flexibility of the trains. The railway network is less dense than the road network which results in a difference in the accessibility of the train network per zone.

Speed

Trains can reach high speeds in terms of technology (65-90 km/h). However, most times the maximum speed is not reached. This is due to the passenger trains on the network and the long braking distance that the driver has to take into account. Next to that, (un)loading takes a lot of time, customs clearance is inefficient and the shunting and switching of locomotives causes a loss of time (Islam & Zunder, 2018). This results in an average commercial speed of long intermodal freight trains of 20-40 km/h (Janic, 2008).

2.3.2.1 Rail freight flows

Rail freight transportation is mostly used for international transport. It is the least used mode in the Netherlands when compared to road and IWW. The left part of Figure 2.5 shows the most important freight rail flows through the Netherlands. The right side of the figure shows that the most important NSTR group for rail transport is the NSTR 9 group (miscellaneous). However, this group is large as the unidentifiable products are part of this group. NSTR group 2 (mining) and 4 (ores) follow with 18% and 15% respectively.

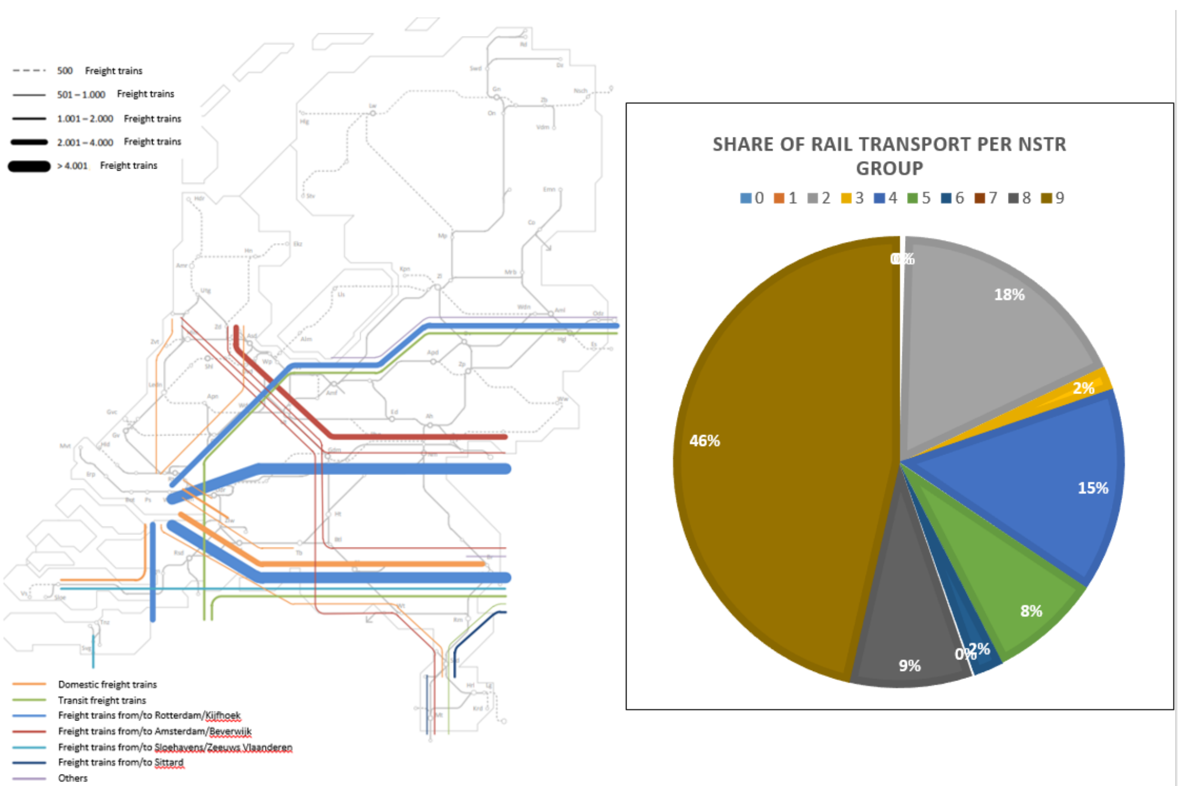

Figure 2.5: Left: Amount of freight trains per OD pair in 2016 (ProRail, 2017). Right: Share of rail transport per NSTR group in 2017 (CBS, 2019d)

2.4 EMISSIONS OF FREIGHT TRANSPORTATION IN THE NETHERLANDS

There is a difference in the emissions of the different modes. Table 2.1 (in chapter 2.1) shows that IWW is the most energy efficient mode, followed by rail and road respectively. Rail has the least emissions of harmful substances and rail and IWW both have a relatively good performance compared to road for the emissions of greenhouse gases. Road scores a 'minus' in all three features, making this the least sustainable mode of the three. Figure 2.6 shows the development of the average CO_2 emissions over the years from 2005 to 2015 per ton kilometre (tkm). The figure clearly shows a difference between the modes, with trucks having 2.5 and 5 times as much CO_2 emissions as IWW and rail respectively.

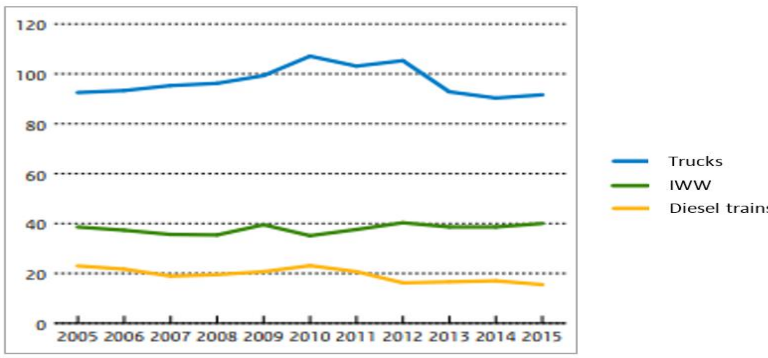

Figure 2.6: Average CO_2 emissions for the modes in grams per ton kilometre on Dutch territory, 2005-2015 (KiM, 2016)

CE Delft (2017$_a$) has calculated the emissions per modality for freight transport in the Netherlands. In the calculations, a difference is made between the tank-to-wheel and the well-to-wheel emissions. Tank-to-wheel (TTW) refers to the emissions produced by the combustion of the fuel during the use of the vehicle while well-to-wheel (WTW) emissions refers to the emissions of the entire energy flow: from the process of extracting fossil fuel or generating electricity to the vehicle driving. The emissions take into account the empty rides. The emissions that are calculated are:

- Carbon dioxide (CO_2): CO_2 is emitted by transportation as a results from the burning of fossil fuels. As CO_2 absorbs infrared radiation, the radiance of the solar heat that reaches the earth to the space is reduced, resulting in global warming.
- PM_c: PM_{10} emissions due to combustion. The particulate matters can form a health risk when inhaled.
- Mono-nitrogen oxides (NO_x): NO_x leads to the formation of smog, environmental acidification and respiratory damage.

In the following sections, the emissions of the different modes are discussed.

2.4.1 Emissions of unimodal transportation

When only one mode is used for the transportation of the freight, the emissions of only that mode are taken into account. For the emissions of the unimodal transportation, in this research only the emissions of using the road are considered, which has the highest CO_2 emissions per ton kilometre (tkm) when compared to rail and IWW (Jonkeren et al., 2019). The representative emissions for road freight transportation are shown in Table 2.3.

Commodity	Vehicle/Vessel	Type of freight	CO_2 (g/tkm) (WTW)	PM_c (g/tkm) (TTW)	NO_x (g/tkm) (TTW)
Bulk	Large van	Med.-weight	1,153	0.148	5.03
	Truck, medium-size	Med.-weight	259	0.017	1.75
	Tractor-semitrailer	Med.-weight	82	0.003	0.29
Container	Tractor-semitrailer, heavy (2TEU)	Med.-weight	102	0.004	0.36

Table 2.3: Representative emission factors for road, per commodity types (CE Delft, 2017$_a$)

2.4.2 Emissions of multimodal transportation

For multimodal transportation, more types of emissions must be taken into account. There are three processes (i.e. drayage, long-hauling and terminal operations) which all result in their emissions (Kim & van Wee, 2015). The emissions factor of trucks are used in the drayage part of intermodal freight systems. For the long-hauling part of the process, the emissions of barges or trains are used. In this research, the emissions of terminal operations are not taken into account.

2.4.2.1 IWW emissions

Table 2.4 shows the representative emissions of IWW. Most of the freight that is transported by IWW is heavy freight. The table shows that for both the bulk and container transportation, the difference of emissions differs per ship type (21 - 38 for bulk and 24 - 44 for container freight transportation).

Commodity	Vehicle/Vessel	Type of freight	CO_2 (g/tkm) (WTW)	PM_c (g/tkm) (TTW)	NO_x (g/tkm) (TTW)
Bulk	Rhine-Herne canal (RHC) vessel	Heavy	38	0.02	0.46
	Large Rhine vessel	Heavy	21	0.01	0.23
Container	(RHC) vessel (96 TEU)	Med.-weight	44	0.02	0.53
	Large Rhine vessel (208 TEU)	Med.-weight	24	0.01	0.26

Table 2.4: Representative emission factors for IWW, per commodity type (CE Delft, 2017$_a$)

2.4.2.2 Rail emissions

Table 2.5 shows the representative emissions of freight transported by rail. 70-90% of the rail freight is transported by an electric train (ProRail, 2017). As electricity does not emit emissions during the use, the TTW emissions are zero. However, the electricity must be generated which results in emissions in the category WTW.

Commodity	Vehicle/Vessel	Type of freight	CO_2 (g/tkm) (WTW)	PM_c (g/tkm) (TTW)	NO_x (g/tkm) (TTW)
Bulk	Electric, medium-length	Heavy	10	0	0
	Diesel, medium-length	Heavy	18	0.01	0.19
Container	Electric, long (90 TEU)	Med.-weight	16		
	Diesel, long (90 TEU)	Med.-weight	30	0.01	0.31

Table 2.5: Representative emission factors for rail, per commodity type (CE Delft, 2017$_a$)

2.5 CONCLUSION FREIGHT TRANSPORTATION IN THE NETHERLANDS

As the characteristics of the modes and the current flows are explained in this chapter, some conclusions can be drawn. The first conclusion is that freight transportation over the road is used the most. The road mode has the largest share in the modal split which has always been a large difference with IWW and rail (see Figure 2.7). However, the modal split does change per NSTR group, with construction and foodstuffs dominating the road transport, oil and ores having the largest share of IWW and mining and ores being important to rail transport. When looking at the geographical distribution, South Holland is the province that processes the most freight.

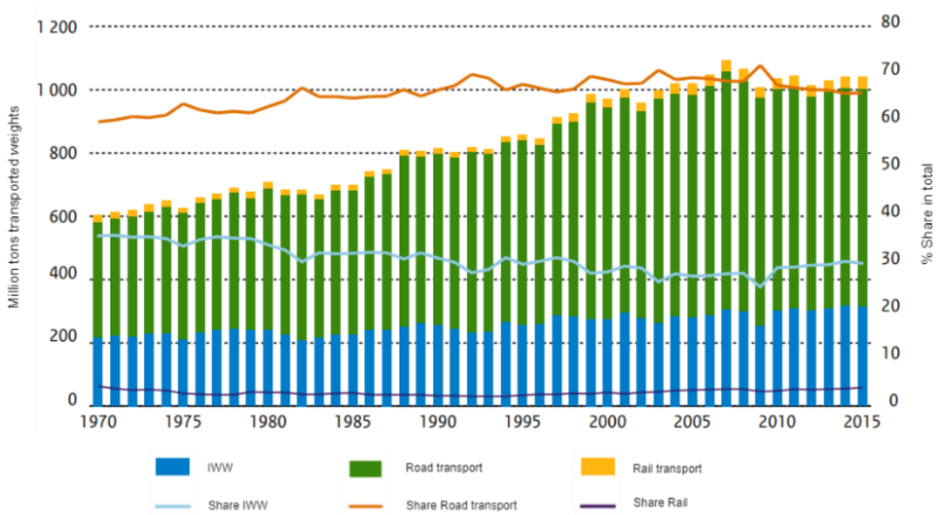

Figure 2.7: development freight transport and modal split in the years 1970 - 2015 (KiM, 2016)

Considering emissions, a difference can be seen between the modes: trucks emit up to 2.5 and 5 times more CO_2 than IWW and rail respectively (see Figure 2.6). This means that the mode that emits the most emissions has the largest share while the mode that emits the least emissions has the smallest share of the modal split, resulting in an unsustainable distribution. The further chapters of this research explore the effects of carbon pricing on this unsustainable distribution, the effects on the emissions per mode and analyse the impact of introducing alternative fuels as an option for the road mode.

3 STRUCTURE OF THE ANALYSIS

Chapter 2 has explained the current situation. This chapter elaborates on the methodology on how to analyse the effects of carbon pricing on the freight transportation in the Netherlands. The structure of the analysis is shown in Figure 3.1. The approach researches how the carbon price might stimulate the reduction of the CO_2 emissions. To simulate this, the influence of the carbon price on three areas is researched. First, the influence of the carbon price on the energy generation market is explained in chapter 3.2. Subsequently, the influence on the choice of fuel by using a vehicle choice model is explained in chapter 3.3. Thereafter, in chapter 3.4, the use of a freight transportation model is explained to be able to research the influence of the carbon price on the choice of the transportation mode. The chapter ends with an explanation of two possible other impacts that are not considered

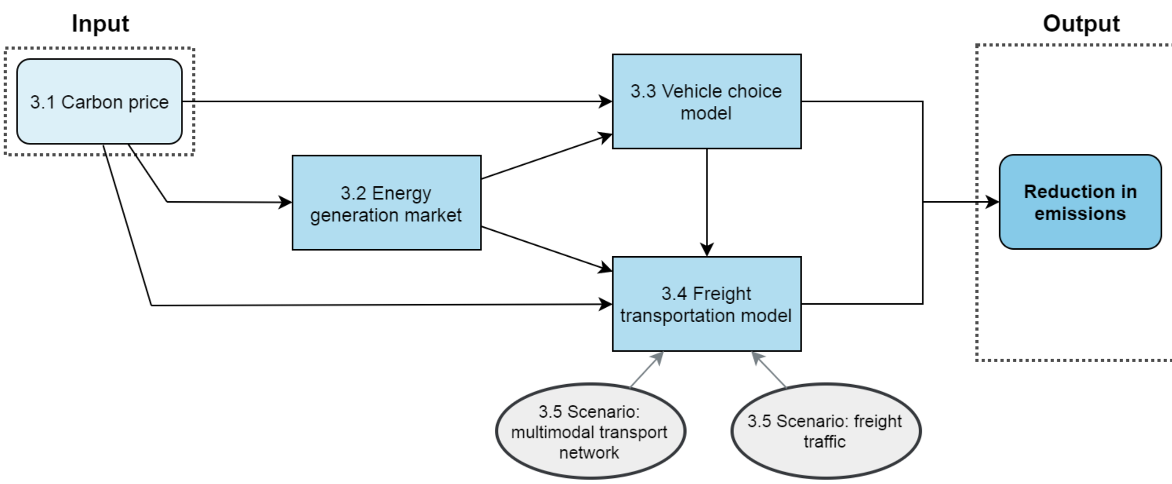

Figure 3.1: Structure of the emissions analysis

3.1 PRICING CARBON FOR TRANSPORT

Introducing a carbon price can be used for the stimulation of a more sustainable transportation system. However, setting a price for emissions has been found to be difficult: "Pricing carbon in a low value does not support the environment, and pricing in a high value negatively affects installed capital and existing consumption patterns" (Bakhtyar et al., 2017). Table 3.1 shows that the prices of carbon differ per organization. CE Delft (2018) determined the environmental prices for the average atmospheric emissions in the EU28 to €22-€94 while the expected price for carbon in the ETS system is €12.4-€79.6 (PBL, 2018). In 2017, the carbon pricing leadership coalition has determined that the carbon price should be US$50-$100 per ton CO_2 in 2030 to achieve the Paris temperature target.

Source	Lower	Central	Upper
CE Delft (2018)	€22	€57	€94
PBL(2018) ETS expected price in 2030	€12	€46	€80
Carbon pricing leadership coalition (2017) expected price in 2030	€40		€90

Table 3.1: Estimated prices of carbon per source

To be able to research the influence of the carbon price on the freight transportation system, the costs of a ton CO_2 are varied in the different scenarios. In this study, the price starts from €0 and is increased in steps of €10 until €500 is reached. The maximum price seems to be unrealistic when compared to the findings in Table 3.1. Nonetheless this price is introduced to fully understand the influence of the price on the system.

3.2 THE INFLUENCE OF THE CARBON PRICE ON THE ENERGY GENERATION MARKET

When the carbon price increases, an extra incentive in becoming more sustainable is introduced. This can lead to a more sustainable way of generating energy. This section first explains the influence on the increase of the efficiency of conventional diesel vehicles, followed by the influence on the generation of electricity.

3.2.1 Influence of the carbon price on the increase of the efficiency of conventional diesel vehicles

The emissions of the current diesel engines of the transportation modes can become more sustainable due to technological improvements. In this study it is assumed that when carbon pricing is introduced, a reduction of CO_2 emissions is reached due to improvements in the technology of trucks, barges and trains.

For the road mode, TNO (2018) found that the CO_2 emissions from conventional diesel vehicles can be reduced by 28% to 33%. TNO also studied the extra costs that are necessary to achieve that reduction. At a cost of €30,000 the CO_2 reduction would lead to 33%. For IWW, a green deal was made that has the goal of decreasing the CO_2 emissions by 40% (Rijksoverheid, 2019). For Rail, the International Union of Railways (2016) states that a decrease of emissions of between 20% and 30% is possible by an increase of the efficiency. To reach this, the designs of the trains should be improved and the use of new technologies should be adapted.

In this study, the assumption is made (in lack of a relation found in the available literature) that the maximum reductions of the modes are achieved at a carbon price of €500 and the decrease is linear. Even though this study assumes the decrease of the emissions, the way the decrease is accomplished in terms of technology is not taken into account. The resulting decrease of the emissions is shown in Figure 3.2.

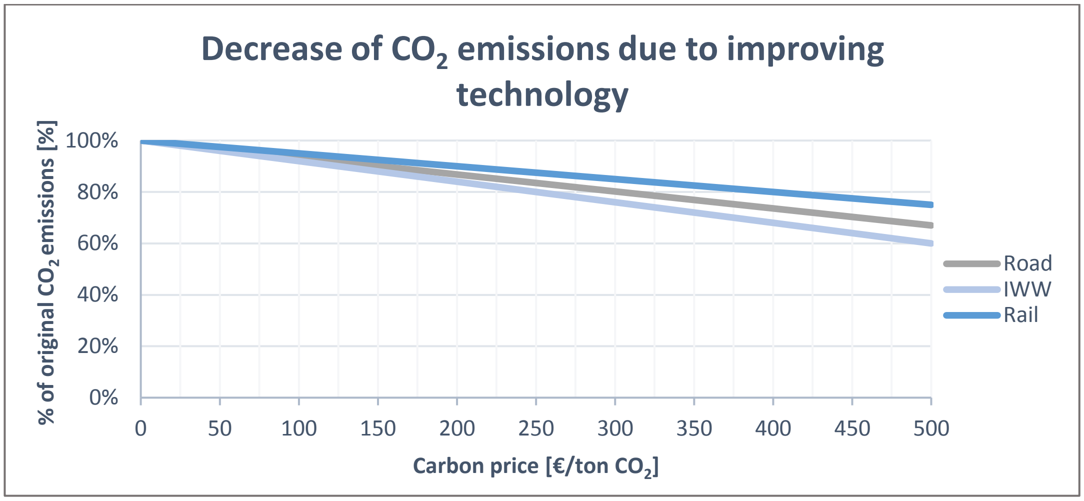

Figure 3.2: Decrease of CO_2 emissions by the different modes

3.2.2 Influence of the carbon price on the generation of electricity

CE Delft (2017_b) states that the costs of unsustainable production of electricity will increase when the carbon price increases. This leads to the "fuelswitch-effect" which reduces the CO_2 emissions of electricity production. De Vrijer & Akkerman (2019) state that when renewable sources would be used, the CO_2 emissions would be much lower (when using wind and sun energy, the CO_2 emissions would be almost 0). Therefore, it is assumed that when the carbon tax increases, more renewable sources will be used to produce electricity, resulting in a reduction of emissions.

To be able to determine the fuelswitch-effect, a relationship between the carbon price and the emission level of electricity must be found. Levin et al. (2019) researched the influence of carbon tax on the generation of energy and found a decrease in the generation of coal and an increase in the generation by wind when the carbon price increases (see Table 3.2).

Carbon tax level	**\$0**	**\$20**	**\$40**	**\$60**	**CO_2/kWh [kg]**
Solar	5,199	5,280	5,250	5,152	0
Wind	12,381	16,762	19,883	21,544	0
Natural gas combustion turbine	1,471	1,109	813	1,225	0.483
Natural gas combined cycle	17,614	20,231	20,387	19,044	0.334
Coal	11,080	4,362	1,411	779	0.837
Nuclear	4,500	4,500	4,500	4,500	0
Total	**52,245**	**52,244**	**52,244**	**52,244**	

Table 3.2: Average annual generation output (MWh) of each unit type per carbon tax level (Levin et al., 2019)

To be able to find the related decrease in CO_2 emissions, the CO_2 emissions per kWh are used per generation type (see Table 3.2). When this is combined with the changes in the shares of the generation types, the following CO_2 emissions are found per carbon tax level:

Carbon tax level	$0	$20	$40	$60
Solar	0	0	0	0
wind	0	0	0	0
ngct	710.31	535.51	392.58	591.52
ngcc	5,882.56	6,756.56	6,808.66	6,360.13
coal	9,269.45	3,649.22	1,180.43	651.71
nuclear	0	0	0	0
Total	15,862.31	10,941.28	8,381.66	7,603.36
Percentage	100%	69%	53%	48%

Table 3.3: CO_2 emissions [x1000 kg] per carbon tax level (Authors table)

To be able to use the decreasing emissions in the study, the relation is extrapolated to a situation of a carbon price of €500. An exponential trend line is plotted using the exchange rate of 1.104 (€1 = $1.104) which results in the line that is shown in Figure 3.3. This line contains a R-squared value of 0.94.

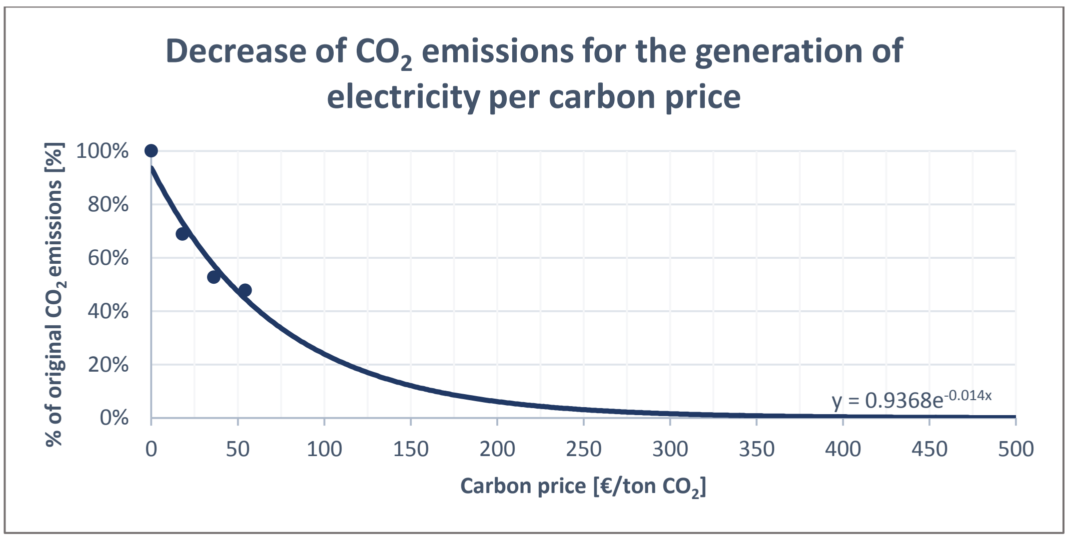

Figure 3.3: Decrease of CO_2 emissions for the generation of electricity per carbon price

The line has the following formula which is used for the decrease in emissions that is caused by the fuelswitch-effect:

$$e_v^x = e_v^0 * e^{-0.014x} \qquad \textit{(Eq. 1)}$$

With:

e_v^x : The emissions of a vehicle kilometre at carbon price x [CO_2/km]

e_v^0 : The emissions of a vehicle kilometre at a carbon price of 0 [CO_2/km]

x : The carbon price [€/ton CO_2]

3.3 Vehicle choice model

The second area that is researched is the potential use of alternative fuels. The carbon price is based on the emissions of the transportation modes. The amount of emissions per mode depends on the fuel that is used. When an unsustainable fuel is used, the price of the transportation increases a lot. Therefore, alternative fuels vehicles (AFVs) that emit less will become a more attractive option, looking from a cost perspective. In this study, the battery electric vehicle (BEV) and the hydrogen fuel cell vehicle (HFCV) is researched.

A BEV is a truck powered by electricity from batteries. Sen et al. (2017) performed a life cycle analysis with different heavy duty freight vehicles trucks in the United states and found that the best alternative fuel truck was the battery electric truck (in terms of costs and emissions). For these trucks, a battery is needed, which has the disadvantage that high capacity batteries are not yet available or are too expensive. However, Liimatainen et al. (2019) performed a literature analysis and found that several studies conclude that “electric trucks are competitive if annual mileage is high enough and battery lifetime matches the vehicle lifetime”.

A hydrogen fuel cell vehicle (HFCV) uses hydrogen (H_2) to produce energy. An important advantage of fuel cell vehicles is that the range of HFCVs is larger than battery electric vehicles (Thomas, 2009) and the fuelling times are comparable to conventional vehicles (Talebian at al., 2018). However, hydrogen vehicles are expensive and can be dangerous when in contact with other substances.

As the costs and the maximum distance driven by alternative fuels differs, it differs per distance which fuel is cheaper. To be able to determine at which carbon price and at which annual mileage the AFVs are becoming a more attractive option than diesel vehicles, a vehicle choice model is used. For this research it must be possible to introduce the carbon price to the vehicle choice model. Next to that, the comparison between diesel vehicles and AFVs must be possible to make.

In this study, the all-or-nothing (AON) algorithm is used for the determination of the fuel type. The vehicle with the lowest total costs is chosen. To be able to use the AON algorithm, it must be assumed that the same attributes are considered and that the transport planners weigh them in the same way. This results in that every transport planner makes the same decision (Ortúzar & Willumsen, 2011). The vehicle choice model that is used in this study is explained in chapter 4.1.

3.4 Freight transportation model

When a carbon price is introduced, the transport operation will become more expensive, with the less sustainable modes getting more expensive than the more sustainable modes. Therefore, the carbon price will influence the choice of the transportation mode. To be able to see the influence that the carbon price has on the choice of modes, a freight transportation model is used.

The freight transportation model is used to simulate the trade-off that transport planners make in the choice between the modes. Therefore, the factors that they take into account should be included in the model. Next to that, the freight transportation model must be able to introduce a carbon price to the model and be able to show the influence of the carbon price on the mode choices.

In this study, a discrete choice model is used as a freight transportation model. Discrete choice models use the concept of "utility" to represent the attractiveness of the alternatives. The characteristics of the alternatives result in, together with the importance of the characteristics, the utility of the alternative. Subsequently, this utility is contrasted to the utilities of the other alternatives to predict whether an alternative is chosen, resulting in a probability value between 0 and 1 (Ortúzar & Willumsen, 2011). These models "are widely used to estimate consumer preferences for transportation options and to simulate choices under various scenarios" (Yip et al., 2018). The freight transportation model that is used in this study is explained in chapter 4.3.

3.5 SCENARIO DEVELOPMENT

As the previous sections have described, the carbon price may affect the transport emissions via several mechanisms. This research focuses on the areas described above. However, other sectors may be impacted as well. In this section, two possible developments of the freight transportation system are described.

3.5.1 Freight traffic scenarios

The freight traffic scenario refers to the flows between the origins and destinations. When a carbon price is introduced, the price of transportation increases which can lead to a decrease of freight demand (Beuthe et al., 2013). In this model, the effect of the carbon price on the production and consumption of the zones is not taken into account. This is an important simplification of the model as in reality the production and consumption will be influenced by the increasing price of transportation.

3.5.2 Multimodal transport network scenario

The multimodal transport network refers to the infrastructure that is needed for the modes to be able to execute the transportation. When new infrastructure is built, travel times of modes can decrease or a mode can become available in the region (e.g. when a new rail line is constructed). A carbon price can lead to investments in the infrastructure, which can lead to an increase in the use of a particular mode. In this study, the current available multimodal transport network is adopted and changes to the network are not taken into account.

4 THE MODELS

The previous chapter described the structure of the analysis. Two models were discussed that are needed for the analysis: the vehicle choice model and the freight transportation model. This chapter explains the selection and the structure of the chosen models. First, the vehicle choice model is explained in chapter 4.1. Subsequently, the freight transportation model is selected in chapter 4.2. In chapter 4.3 the selected model is explained. The chapter ends with the explanation on how the models are combined for the analysis and how the reduction of emissions is determined.

4.1 VEHICLE CHOICE MODEL: THE TCO MODEL

The vehicle choice model is used for modelling the choice of the vehicle type for road freight transportation. In this study, the Panteia TCO (total cost of ownership) model is used for the choice of the vehicle type: Diesel, BEV or HFCV. The Panteia TCO model was made for the comparison of the TCO of BEVs and diesel vehicles for several vehicle types.

4.1.1 The structure of the TCO model

The Panteia TCO model calculates the total cost of ownership by adding up different types of costs. As an input, the model needs the following factors:

1. **The type of vehicle**: choice from small delivery van, medium-sized delivery van, medium-sized delivery van luxury, large delivery van, small truck, big truck and a truck trailer.
2. **The average mileage per year**: the amount of kilometres that a truck drives per year.
3. **The days of operation per week**: it is assumed that this is 5 days per week.

Using these factors, the costs per year are calculated. Four scenarios are calculated:

- Downtime charging only: refers to the situation that charging the battery is only done when the vehicle is at the depot.
- Opportunity charging only: refers to the situation that charging the battery is only done when an opportunity arises and not at the depot.
- Opportunity charging if needed: refers to the situation that charging the battery is done at the depot or when an opportunity arises.
- Diesel: Diesel refers to the conventional vehicles using diesel as fuel.

For each scenario, the model calculates several costs. Table 4.1 shows which costs are included in the model. By adding up the different type of costs, the costs per km and per hour are determined for the given mileage per year.

Factor	Represents
Fixed cost per year	Vehicle road tax Toll Interest (vehicle purchase loan) Insurance Misc. Vehicle costs
Variable costs per km	Depreciation costs (vehicle) Depreciation costs (battery) ***Carbon tax*** Tires Fuel Electricity Repair/Maintenance
Special transportation costs	-
Private charging system, fixed cost per year	Purchase & installation Operational costs
Driver costs	Hourly Wage Allowances Other costs
General costs (overhead)	Salary costs Building Misc.

Table 4.1: Overview of which costs are taken into account in the Panteia TCO model

4.1.1.1 Introducing the costs of emissions to the TCO model

To be able to determine when electric driving becomes cheaper, the carbon price is introduced to the TCO model. The carbon price is added to the TCO model by adding the costs to the factor "variable costs per km" (see Table 4.1). When the carbon tax is added, the costs per km and the costs per hour are calculated for the different scenarios. With this information, it can be determined whether using electricity or hydrogen as fuel is cheaper than diesel for the given mileage per year. To realize this, the following inputs are used:

- The type of vehicle: the truck-trailer is chosen for the vehicle type. This category represented 69.47% of the Dutch freight vehicles in 2017 (CBS, 2018_b).
- The average mileage per year: In this input variable, the distance ranges are tested. The distance range will be increased in steps of 5,000 km per input to determine when electricity becomes cheaper than diesel. The maximum is 166,000 km per year for a truck-trailer.
- The carbon tax per vehicle kilometre: chapter 4.4.2 explains how the carbon tax per vehicle kilometre is determined.

To simulate the effect of the carbon price on the use of HFCVs, the costs of these vehicles are added to the Panteia TCO model. This analysis is shown in appendix E. However, as the analysis describes, the HFCVs do not become an economically viable option within the carbon price range. Therefore, the HFCV option is not further elaborated in the study.

The maximum distance that an electric vehicle can drive without charging is determined by the factors of the battery in the TCO model that are shown in Table 4.2. These factors lead to a maximum range of 150 km for an electric truck trailer before the battery has to be charged again.

Type of vehicle	Truck trailer
Battery	320 kWh
Usage of electricity	1.75 kWh/km
Depth of Discharge (DOD)	80%
Maximum Range	**150 km**

Table 4.2: Factors for the calculation of the maximum distance of electric vehicle (Panteia TCO model)

The outcome of this analysis is the mileage per year where using an alternative fuel is as expensive as or cheaper than using diesel per carbon tax level, considering the distance costs [€/km].

4.2 Analysis of available freight transportation models and the selection of BasGoed

In the Netherlands the BasGoed, the LMS, the BIVAS and the NEMO models are used for the estimation of the freight distribution in the Dutch network system. The models are explained below, followed by an analysis of which model is the most suitable for this research.

4.2.1 BasGoed

BasGoed ("Bas" = "basic" and "Goed" = "good") is a model that estimates the production and consumption of zones within the Netherlands and some zones outside of the Netherlands. The model estimates these productions and consumptions per commodity group. The NSTR1 commodity group index is used which means 10 commodities are distinguished. Next to that, the model uses the multinomial logit model to estimate the modal split. Using this modal split, the number of rides is calculated for road traffic (de Jong et al., 2011).

4.2.2 LMS

The LMS ("Landelijk Model Systeem" meaning "national model system") is used for estimating the load on the network in the Netherlands. The road and public transport network, the number of inhabitants, the amount of households and other demographic information is used for the base year and the forecast year as input. The model uses 1379 zones in the Netherlands and focuses on passenger transport (Rijkswaterstaat, 2017).

4.2.3 BIVAS

BIVAS ("binnenvaart analyse systeem" meaning "inland waterway analysis system") is a model that focuses on inland shipping. BIVAS is used to perform network analyses of the Dutch waterway network. The load on the waterways can be determined and scenarios can be included (BIVAS, n.d.).

4.2.4 NEMO

NEMO has replaced RoutGoed as the model for the estimation of the Dutch railway system. The model uses an OD (origin-destination) matrix and calculates the amount of train wagons that are needed to perform the transport. With the information about the train wagons, the amount of trains are determined. Subsequently, the model uses the travel times and distances between the COROP zones to determine the amount of trains on the network (ProRail, 2013).

4.2.5 Analysis

The models described above differ in characteristics. Table 4.3 shows an analysis to explore which method is most suitable for this research. The analysis focuses on several criteria that have different weights of importance:

- Focus on freight transport (30%): as this research focuses on freight transportation, the model should focus on the considerations that are used for freight transportation.
- Focus on multimodal transport (30%): A consideration should be made between different modes. Therefore, the model has to focus on the multimodal transport perspective.
- Distinguish several commodity groups (20%): Differences may occur between several commodities. Therefore, the model should focus on different commodity groups.
- Focus on emissions (10%): As this research analyses the emissions of the modes, the model should focus on the emissions of transportation modes.
- Amount of zones (10%): When more zones are introduced, the research can become more detailed. A model with many zones can contribute to the detail level of the research.

The table uses a rate from 1 to 2 with 1 being the worst and 2 being the best. Using the weights of importance, the resulting score is calculated. The table shows that BasGoed is the most suitable model to use for this research. The model focuses on multimodal freight transportation in the Netherlands and distinguishes several commodity groups. However, the model does not have a focus on the emissions. The BasGoed model is explained further in the next section of this chapter, followed by an explanation on how the focus on emissions is added to the model.

Criteria/ Model	Focus on freight transport (30%)	Focus on multimodal transport (30%)	Distinguishes commodity groups (20%)	Focus on emissions (10%)	Amount of zones (10%)	Score
BasGoed	2	2	2	1	1	**1.8**
Bivas	2	1	2	2	1	**1.6**
LMS	1	1	1	1	2	**1.1**
NEMO	1	1	1	1	1	**1**

Table 4.3: Analysis of available current models (Authors table).

4.3 THE BASGOED MODEL

BasGoed was developed in the years 2010-2011 and was made for the Dutch MoT (Ministry of Transport). The model includes road, rail and IWW transport and was made because the need was raised for a more simple and straightforward model as the SMILE(+) model was hard to maintain (de Jong et al., 2013). BasGoed is a model that estimates the production and consumption of zones within Europe and the associated transportation flows per mode. In the Netherlands the model uses 40 zones. Figure 4.1 shows the structure of the model.

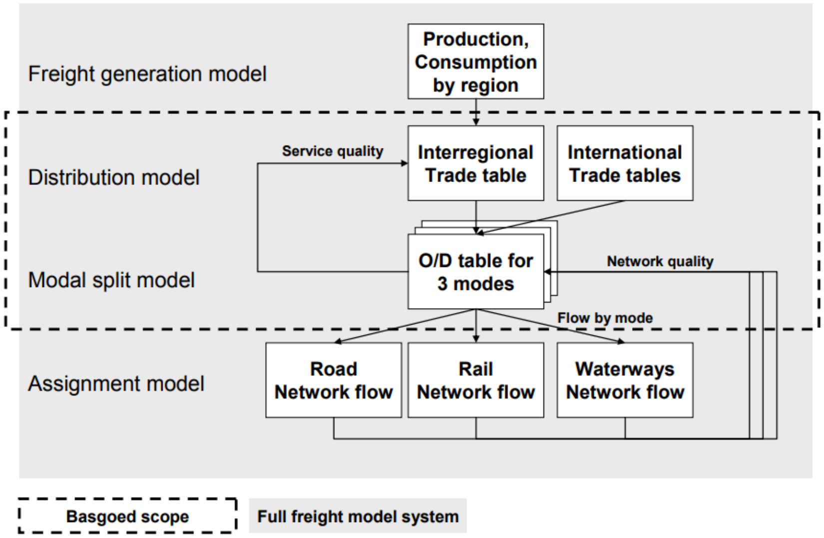

Figure 4.1: Structure of BasGoed (de Jong et al., 2011)

The BasGoed model is based on the four step freight modelling approach (Ortúzar & Willumsen, 2011):

1. Freight generation: yearly volumes of freight produced and consumed
2. Distribution: transport flows between regions
3. Modal split: flows between regions by mode
4. Traffic conversion and assignment: number of vehicles on the road

As Figure 4.1 indicates, the freight generation and the assignment model fall out of scope for the model as other existing models are used for these steps; the freight generation is performed by SMILE+ and the assignment is performed by NEMO (rail), BIVAS (IWW) and LMS/NRM (road). These models are used to identify possible bottlenecks in the freight transport system in the future which is used by the MoT (de Bok et al., 2017). To understand the structure of the models that BasGoed uses, the distribution and modal split modules are elaborated below.

4.3.1 The Distribution module in BasGoed

The distribution module produces OD matrices for the forecast year which thereafter is used as input for the modal split module. The distribution is calculated for the base year and the forecast year, both leading to synthetic forecasts. These synthetic forecast are used as input for the growth model to calculate the forecast distribution. Figure 4.2 shows the structure of the distribution module in BasGoed.

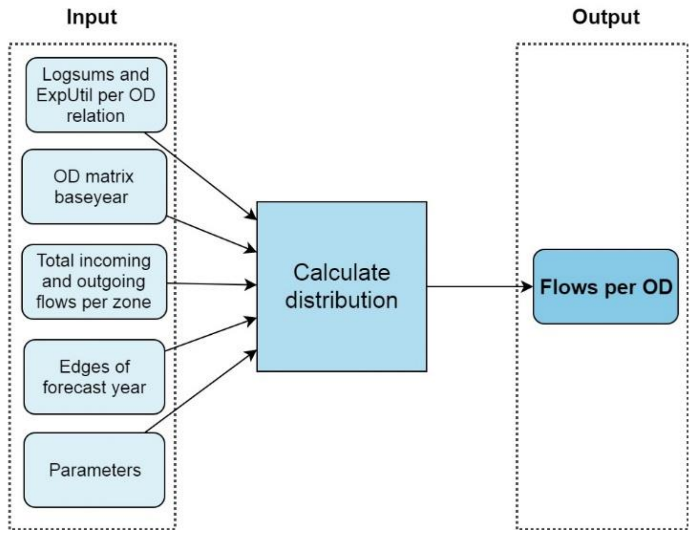

Figure 4.2 Distribution module structure (Authors figure)

Several input data is needed to be able to calculate the distribution of the OD-pairs:

1. **The logsums and ExpUtil per OD relation**: this data is retrieved from running the modal split module. The logsums and ExpUtil express the accessibility of the destinations using the level of services of OD-pairs.
2. **The OD matrix of the base year per commodity type**: the OD matrix is retrieved from the Basisbestand goederenvervoer (Basic file freight transport). This data gives information about the flows of the OD pairs in the base year.
3. **The total incoming and outgoing flows per zone in the forecast year per commodity type**: the total incoming and outgoing flows per zone are retrieved from the freight generation module. This is the information about the production and the consumption per zone.
4. **Edges of the forecast year**: the edges are retrieved from the economy module and refer to the maximum increase. The edges are determined by calculating the total amount of tons per OD-pair and determining the row and column total of the first converted base matrix.
5. **Parameters**: the parameter alpha is used for determining the ‘resistance’ in the gravity model. These parameters differ per NSTR group and are retrieved from the parameters file as standard values.

By using a gravity model, the growth factors are calculated. These are applied to the base year OD matrix. The tons per OD-pair can then be determined (de Jong et al., 2011). This results in a synthetic forecast of the distribution, which is used as input for the growth model (explained in 4.3.1.1).

4.3.1.1 Growth model

As introduced in the Distribution module, the calculated synthetic forecast is not adopted as the final forecast. For determining the final forecast, an extra growth factor is calculated in the growth model. The growth model determines the final forecast by determining the growth factor between the synthetic base year and the synthetic forecast year. The base year is multiplied by this factor which results in the forecast. The formula for the growth model is:

$$F = \frac{F'}{B'} * B \qquad \textit{(Eq. 2)}$$

With:

F : Forecast year freight flows
F' : Synthetic forecast
B' : Synthetic Base year
B : Base year freight flows

The growth model is applied both after the distribution module and after the modal split module. The growth model has many exceptions for when one of the numbers is zero or cases where the number falls outside of desired limits.

4.3.2 The Modal split module in BasGoed

The modal split module predicts the market share of the three modes (rail, road and IWW) for each OD pair. The structure of the modal split module is shown in Figure 4.3. Several data is used as input to calculate the utilities. These utilities are then used for the calculations of the transport volumes and the logsums. The outputs of the module are the totals per mode (modal split) and the logsums. The totals per mode are used for the modal split while the logsums are used in the distribution module. The different parts of the calculation of the totals per mode are explained next.

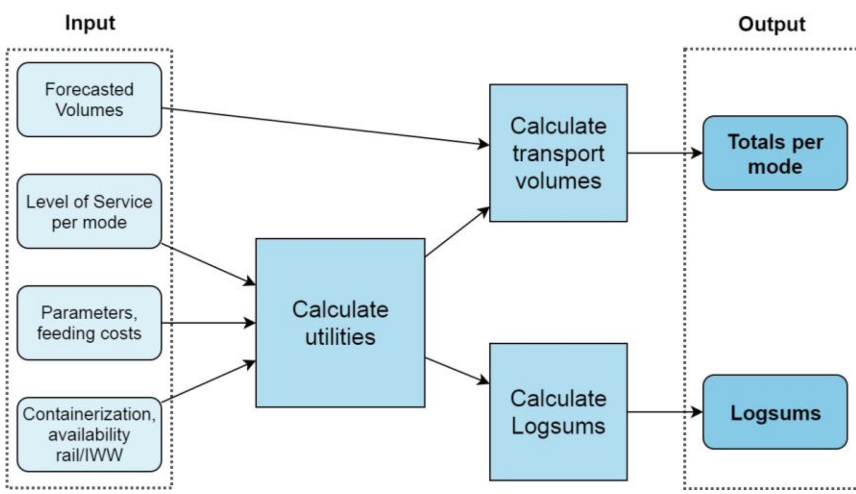

Figure 4.3: Modal split module structure (Authors figure)

4.3.2.1 Calculating the utilities

For the calculations of the utilities, the utility function is used. The utility function for transporting one vehicle of commodity g between origin i and destination j by mode v is specified as (Rijkswaterstaat, 2018):

$$V_{i,j,v,g} = \beta^{c}{}_{g} \cdot c_{ijvg} + \beta^{t}{}_{g} \cdot t_{ijvg} + \beta^{cont}_{vg} \cdot CONT_{ijg} + \beta^{br}_{vg} \cdot d^{br} + \beta^{i}{}_{ivg} + \beta^{j}{}_{jvg} \qquad \textit{(Eq. 3)}$$

With:

$\beta^{c}{}_{g}$: Cost parameter for commodity g

c_{ijvg}	:	The costs for transporting commodity g from i to j with mode v
$\beta^{t}{}_{g}$	:	Time parameter for commodity g
t_{ijvg}	:	The time for transporting commodity g from i to j with mode v
β_{vg}^{cont}	:	Containerization parameter for commodity g with mode v
$CONT_{ijg}$	:	Containerization degree for OD pair i, j and commodity g
β_{vg}^{br}	:	Parameter for crossing a border for commodity g with mode v
d^{br}	:	Dummy variable for crossing a border (1 if a border is crossed, 0 otherwise)
$\beta^{i}{}_{ivg}$	:	Origin (i) and mode (v) specific constants for commodity g
$\beta^{j}{}_{jvg}$	:	Destination (j) and mode (v) specific constants for commodity g

To be able to use the function, several inputs are needed. The required information is explained next.

4.3.2.1.1 Level of service per mode in the utility function

To be able to determine the modal split, the levels of services of the different modes are used. The level of service refers to the distance, cost and time of the different modes. The utility function shows which levels of services are taken into account:

- The costs for transporting commodity g from i to j with mode v
- The time for transporting commodity g from i to j with mode v

To be able to retrieve the information, data from other existing models is used. For the information about the mode 'road', the information about travel distance and travel time is obtained from LMS. The LMS has split the day in three parts as this model considers the congestion and number of users on the road. As BasGoed does not work with these three parts in a day, the weighted average is calculated to retrieve the average of the day. Next to that, LMS has more zones than BasGoed. Therefore, the zones are combined to get the information in the COROP zones index. The weighted average is calculated using the following formula (de Jong et al., 2010):

$$C_{ij} = \frac{\sum_{i=1,j=1}^{n} t_{ij} * c_{ij}}{\sum_{i=1,j=1}^{n} t_{ij}} \qquad \textit{(Eq. 4)}$$

With:

i : Origin i
j : Destination j
C_{ij} : Costs to go from i to j (time or distance)
c_{ij} : costs to go from i to j in the LMS (time or distance)
t_{ij} : Amount of tours from i to j

For the rail mode, the information (i.e. travel time and distance) is obtained from the Routgoed model. In Routgoed, the COROP index is used for the zones, which means no adjustments were needed in the zones that are used. Routgoed gives the information about the travel time between service stations when travelled by train (de Jong et al., 2010). BasGoed adds the waiting and (un)loading times and feeding costs. The connections of the zones to the RoutGoed network is shown in Appendix D. In some zones there is no service point to the rail network available. In these cases, the zones are connected to the most logical service point in a nearby zone.

The travel times and distances between the service stations for the IWW mode are obtained from the BIVAS model. The BIVAS zones are different to the COROP zones, as can be seen in Appendix D. BasGoed changes the BIVAS zones to the COROP index and uses the average of all travel times and distances. The waiting time for locks are considered in the travelling times of the BIVAS model. For all the distances and times outside of the Netherlands the TRANSTOOLS model is used.

4.3.2.1.2 Costs formula

The distances and travel times of the different modes are used to calculate the costs of using a certain mode for a certain OD-pair for a certain commodity type. The costs to feed the network nodes for rail and IWW are calculated by using the average time and distance that is needed to reach the node. This is based on calculations of the LMS (see equation 4). The costs that are included for rail and IWW are shown in Figure 4.4. The costs indicated in red are not included in the model.

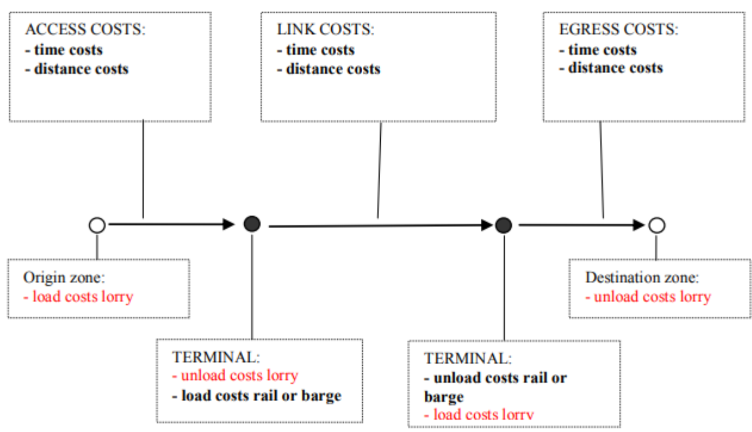

Figure 4.4: Costs that are included for rail and IWW (de Jong et al., 2011).

The formula for calculating the costs for transporting goods between origin i and j with mode v differ per NSTR group:

For NSTR 0, 1, 5, 7, 8 and 9, it is assumed that the freight needs pre- and end drayage. Therefore, the formula is:

$$c_{ijvg} = d_{iv}^{acc} \cdot T_g^{road} + d_{jv}^{egr} \cdot T_g^{road} + d_{ijv}^{itr} \cdot T_{vg} + t_{iv}^{acc} \cdot R_g^{road} + t_{jv}^{egr} \cdot R_g^{road} + t_{ijv}^{itr} \cdot R_{vg} + 2 \cdot Unload_{vg}$$

(Eq. 5)

For NSTR groups 2, 3 and 4 it is assumed that the freight transportation over rail or IWW goes via direct access. This is assumed as mining, oil and ores (NSTR 2, 3 and 4) are most often commodities that have origins and destinations that are located at a rail or IWW service station. This means no feeding costs over the road are considered, which results in the formula:

$$c_{ijvg} = d_{ijv}^{itr} \cdot T_{vg} + t_{ijv}^{itr} \cdot R_{vg} + 2 \cdot Unload_{vg}$$ *(Eq. 6)*

For NSTR group 6 (construction) only the arrival feeding costs are taken into account as it is assumed that the origin of the freight is located at a service station of rail or IWW and the destination is located elsewhere. This results in the formula:

$$c_{ijvg} = d_{jv}^{egr} \cdot T_g^{road} + d_{ijv}^{itr} \cdot T_{vg} + t_{jv}^{egr} \cdot R_g^{road} + t_{ijv}^{itr} \cdot R_{vg} + 2 \cdot Unload_{vg} \qquad \text{(Eq. 7)}$$

With:

d^{acc}	:	Distance to reach access for a train or IWW terminal
T_g^{road}	:	Average distance costs for transporting commodity g over the road
d_{jv}^{egr}	:	Distance from the terminal to the destination
d_{ijv}^{itr}	:	Distance from i to j with mode v
T_{vg}	:	Average distance costs for commodity type g with mode v
t^{acc}	:	Time to reach access for a train of IWW terminal
R_g^{road}	:	Costs per time unit for commodity g over the road
t_{jv}^{egr}	:	Time to transport the goods from the terminal to the destination
t_{ijv}^{itr}	:	Time from i to j with mode v
R_{vg}	:	Costs per time unit for commodity type g with mode v
$Unload_{vg}$	:	Unloading costs for commodity g with mode v

Variables in the cost function

The parameters in the cost function represent the costs of using a modality. These costs consist out of two types of costs: Variable costs and fixed costs. The fixed costs refer to labour and capital costs while the variable costs refer to the fuel and maintenance and repair (Wiegmans & Konings, 2015).

- **Distance costs for commodity type g with mode v:** This parameter represents the costs of using a modality per kilometre. The distance costs are the sum of the variable costs 'average costs' [€/vehicle/km] and the fuel costs [€/vehicle/km]. As this variable refers to the modes, the variable is equal for all the commodities but differs per mode. For multimodal modes (rail and IWW), the pre- and end- Haulage is done over the road. This means that the distance costs of the road also play a role in the total costs for the transportation of multimodal modes. The distance costs differ per scenario.
- **Time costs for transporting the goods**: This parameter represent the costs of using a certain mode per time unit. The parameter is partly based on the value of time for transporting the goods, which differs a lot per mode. The time costs per mode that are used in BasGoed are shown in Table 4.4. The costs are the same for all the NSTR groups and all the scenarios.

	Road	IWW	Rail
Time costs per vehicle [€/hour]	€43.41	€223.47	€569.35
Time costs per ton [€/hour/ton]	€0.0592	€0.0022	€0.0132

Table 4.4: Time costs per mode in BasGoed

4.3.2.1.3 Time formula

Just like the calculations for cost, the calculations for the time for transporting goods between origin i and j with the rail or IWW mode differ per NSTR group. For NSTR 0, 1, 5, 7, 8 and 9 it is assumed that the goods need time to be able to get to the terminal (access time) and time to get from the terminal to the destination location (egress time). This results in the formula:

$$t_{ijv} = t_{iv}^{acc} + t_{jv}^{egr} + t_{ijv}^{itr} \qquad \textit{(Eq. 8)}$$

For the NSTR groups 2, 3 and 4 it is assumed that the freight transportation over rail or IWW goes via direct access. This results in the formula:

$$t_{ijv} = t_{ijv}^{itr} \qquad \textit{(Eq. 9)}$$

For NSTR group 6 (construction) only the arrival feeding costs are considered. This results in the formula:

$$t_{ijv} = t_{jv}^{egr} + t_{ijv}^{itr} \qquad \textit{(Eq. 10)}$$

4.3.2.1.4 Parameters in the utility function

As the utility function shows, several parameters are needed for the different modes. Specific parameters are indicated per commodity group or per mode. An explanation per parameter is given here:

- **Cost parameter for commodity g:** The cost parameter refers to the importance of the costs for the transport planner. When the absolute value of the parameter increases, the costs will become more important in the decision-making process. The parameter differs per commodity group. Table 4.5 shows the cost parameters for the commodities in BasGoed.

NSTR group	Commodity	Cost parameter [utility/€]
NSTR0	Agriculture	-0.0895
NSTR1	Foodstuffs	-0.1923
NSTR2	Mining	-0.0879
NSTR3	Oil	-0.3757
NSTR4	Ores	-0.3900
NSTR5	Basic Metals	-0.0594
NSTR6	Construction	-0.2732
NSTR7	Fertilisers	-0.2254
NSTR8	Chemicals	-0.0970
NSTR9	Miscellaneous	-0.0337

Table 4.5: Cost parameter per commodity [utility/€]

- **Time parameter for commodity g**: This parameter represents the utility that is acquired by the time the goods spend in transportation. This parameter is related to the value of time of the different commodities and thus differs per NSTR group. The value of time of capital costs per commodity type and the associated time parameters that are used in BasGoed are displayed in Table 4.6:

NSTR group	Commodity	Value of time	Time parameter [utility/min]
NSTR0	Agriculture	0.18	-2.64E-04
NSTR1	Foodstuffs	0.21	-6.68E-04
NSTR2	Mining	0.09	-1.37E-04
NSTR3	Oil	-	0.00E+00
NSTR4	Ores	0.16	-1.04E-03
NSTR5	Basic Metals	0.38	-3.76E-04
NSTR6	Construction	0.10	-4.74E-04
NSTR7	Fertilisers	0.16	-6.04E-04
NSTR8	Chemicals	0.21	-3.31E-04
NSTR9	Miscellaneous	0.66	-3.57E-04

Table 4.6: Value of time of capital costs per commodity type (de Jong et al., 2011)

- **Containerization parameter for commodity g with mode v:** The containerization parameter is related to the containerization degree for OD pair i, j and commodity g. The parameter converts the degree of containerization to the amount of utility that the containerization of goods add. Table 4.7 shows the containerization parameters per commodity type and per mode that are used in BasGoed. For the road mode, no utility is retrieved for containerization.

NSTR group	Commodity	IWW	Rail
NSTR0	Agriculture	0.0	0.0
NSTR1	Foodstuffs	-3.7	-12.3
NSTR2	Mining	-12.0	-143.5
NSTR3	Oil	0.0	0.0
NSTR4	Ores	-15.2	0.0
NSTR5	Basic Metals	-3.8	-9.0
NSTR6	Construction	1.0	-154.7
NSTR7	Fertilisers	0.0	-60.9
NSTR8	Chemicals	0.0	2.5
NSTR9	Miscellaneous	6.0	5.8

Table 4.7: Containerization parameter per commodity type per mode in BasGoed

- **Parameter for crossing a border for commodity g with mode v:** This parameter is related to the dummy variable of crossing a border. By using the parameter, the utility is calculated for crossing a border. Table 4.8 shows the parameters per commodity type per mode that are used in BasGoed. For the road mode, no utility is retrieved for crossing a border.

NSTR group	Commodity	IWW	Rail
NSTR0	Agriculture	-0.2	0.0
NSTR1	Foodstuffs	-0.8	-6.3
STR2	Mining	1.1	0.0
NSTR3	Oil	0.0	0.0
NSTR4	Ores	0.0	0.0
NSTR5	Basic Metals	0.6	0.0
NSTR6	Construction	-0.8	0.0
NSTR7	Fertilisers	-0.4	0.0
NSTR8	Chemicals	0.6	-2.5
NSTR9	Miscellaneous	-0.5	-1.5

Table 4.8: Parameters for crossing a border for the commodities per mode used in BasGoed

- **Origin (i) and mode (v) specific constants for commodity g:** The origin and mode specific constants relate to the preference of using mode v when i is the origin of the OD-pair. This preference is not explicable by the costs, time and other aspects that are included in the utility function but can be an important explanatory factor. The constant controls "for unobserved attributes that may be correlated with observed covariates" (Klaiber & von Haefen, 2018).
- **Destination (j) and mode (v) specific constants for commodity g:** This constant has the same explanation as the previous, but refers to the preference of using mode v for a certain destination.

4.3.2.1.5 Other factors

Next to time and costs, other factors also influence the decision of the mode. These factors are discussed below.

- **Containerization:** The containerization variable gives a percentage of the amount of freight that is transported in a container. Most often the chance of using rail or IWW increases when the share of containers increases. The containerization is specific for each OD-pair and each commodity type.
- **Availability of IWW and rail:** The availability of the IWW or rail modes refer to the possibility to using that certain mode for the certain OD-pair. The road mode is available for each OD-pair, while IWW and rail are only available for certain OD-pairs. The availability can be 0 (not available) or 1 (available), with 0 resulting in a chance of 0 to use the mode for that specific OD-pair.
- **Load factor:** The load factor refers to the amount of tons per vehicle per mode. The load factor differs per mode and per scenario but stays the same per NSTR group. The load factor is used for converting the variables from vehicles to tons. Table 4.9 shows the different load factors per mode and per scenario. The scenarios are explained in chapter 4.3.3.
- **Percentage loaded vehicles:** The percentage loaded vehicles represents the percentage of the vehicles that is used for the transportation of goods compared to the empty trips (as the vehicle has to return to its origin at one point). The percentage of the vehicle that is loaded is (together with the load factor) used for converting the variables from vehicles to tons. Table 4.9 shows the percentage loaded vehicles for the different modes in the different scenarios.

Scenario	Road		IWW		Rail	
	Load factor	Percentage loaded vehicles [%]	Load factor	Percentage loaded vehicles [%]	Load factor	Percentage loaded vehicles [%]
Low 2030	17.37	0.693	2561.94	0.663	1053.38	0.673
Low 2040	17.48	0.694	2577.75	0.665	1059.89	0.675
Low 2050	17.59	0.695	2593.56	0.666	1066.39	0.676
High 2030	17.59	0.695	2593.56	0.666	1066.39	0.676
High 2040	17.81	0.698	2593.56	0.666	1079.40	0.679
High 2050	18.02	0.701	2593.56	0.666	1092.40	0.681

Table 4.9: Load factor and percentage loaded vehicles for the different modes in the different scenarios used in BasGoed

- **(Un)loading costs:** The (un)loading costs refer to the costs for loading or unloading the vehicle. The costs are taken from the VKM, the comparison framework for modes, and are divided by the loading degree and the percentage loaded vehicle to calculate the costs per ton. The (un)loading costs are shown in Table 4.10.

	Road	IWW	Rail
Unloading costs per vehicle	€49.01	€2364.18	€6249.18
Unloading costs per ton	€4.01	€8.67	€1.37

Table 4.10: (Un)loading costs per mode

4.3.2.2 Calculating the transport volumes

When the utility of the different modes is available, this can be used to calculate the transport volumes with the modal split function:

$$Volume_{ijvg} = TotalVolume_{ijg} * \frac{\exp(V_{ijvg})}{\sum_{v=1}^{3}\exp(V_{ijvg})} \quad \textit{(Eq. 11)}$$

With:

$Volume_{ijvg}$: Total volume of commodity g between region i and j with mode v
$TotalVolume_{ijg}$: Total volume of commodity g between region i and j
V_{ijvg} : Utility for commodity g between region i and j with mode v

The total volumes of the modes are the result of the modal split module in BasGoed. These volumes are calculated for the base year (Resulting in the synthetic base year) and for the forecast year (resulting in the synthetic forecast year). Subsequently, the results of the synthetic base year and the synthetic forecast year are used in the growth model (explained in chapter 4.3.1.1) to get to the final results.

In this study, the synthetic forecast of the modal split module is used for the results. This means that the growth model is not implemented. It was decided to do so as the growth factor is a tool to correct for different forecasts than the reality. However, when major changes are implemented, this correction is no longer effective. By also implementing the growth model, the mode sensitivity to changes is set back by the corrections.

4.3.3 Scenarios in the BasGoed model

The BasGoed model makes use of six scenarios which are created by PBL (Welfare, prosperity and quality of the living environment), called the WLO (Welvaart en leefomgeving: Welfare and environment) scenarios (Significance, 2015). The scenarios refer to the years 2030, 2040 and 2050. Each year has two scenarios: high and low. This results in the following scenarios for the BasGoed model:

1. Low 2030
2. Low 2040
3. Low 2050
4. High 2030
5. High 2040
6. High 2050

The difference between the high and low scenarios is created by expected differences in economic factors, international policy, logistics development and national policy. The impact between uncertainties for the WLO freight transport and ports are shown in Table 4.11.

	Reference scenario 'High'	Reference scenario 'Low'
World economy	Grows strong	Limited growth
International trade	Grows trend-wise in relation to the global economy	Grows trend-wise in relation to the global economy
Competitive position of Dutch ports in the HLH range and HLH range in Europe	Is retained	Is retained
Sector structure	Relatively strong growth in service sector	Relatively strong growth in service sector
Climate policy	Substantial, major consequences for cargo flows of coal, oil and biomass	Limited, limited consequences for cargo flows of coal, oil an biomass
European transport policy	Trend-wise	Trend-wise
Logistical organization	Strong increase in scale, consolidation and efficiency improvement	Limited increase in scale, consolidation and efficiency improvement
Dutch policy	Minimally differentiated	Minimally differentiated

Table 4.11: Uncertainties in relation to the scenarios (CPB, 2016)

In BasGoed, several factors are dependent on the scenarios. First of all, the amount of freight that is transported differs; a high scenario leads to a larger increase of freight than a low scenario. Next to that, the fuel prices are different per scenario as this is influenced by the policies that are introduced. The technology and efficiency of the freight flows is also different per scenario as this is dependent on the logistical organization (CPB, 2015). This results in different forecasts for the factors in the model. Figure 4.5 shows the difference between the forecasts of the scenarios.

For the analysis in this study, 4 out of 6 scenarios are included: Low 2030 (L2030), High 2030 (H2030), Low 2050 (L2050) and High 2050 (H2050) as for these years goals have been set for the sustainability and emissions.

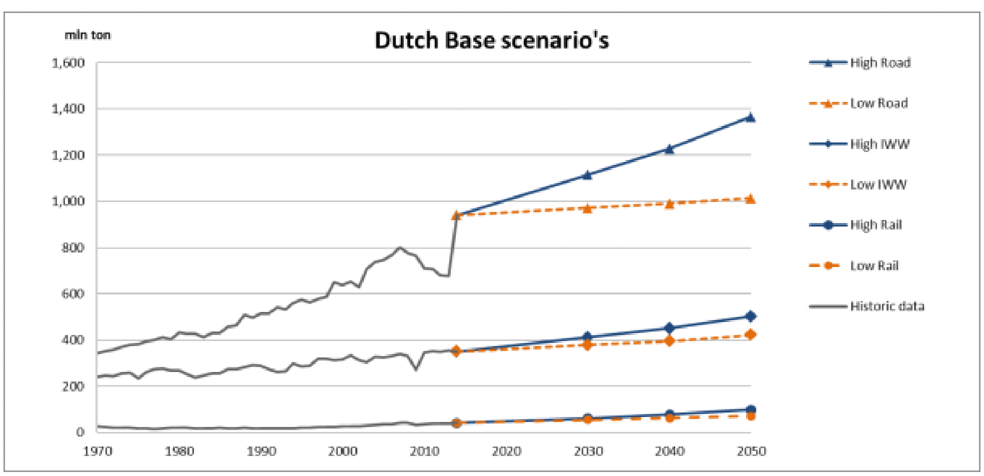

Figure 4.5: The Dutch Base Scenarios and their forecasts in million tons (de Bok et al., 2017)

4.4 Introducing alternative fuels and emissions to the modal split module in BasGoed

In the current BasGoed model (v3.0) emissions of modes are scarcely included. For the road and rail mode, the emissions are not included. For IWW, the BasGoed model has taken into account a carbon price in the high scenario. This scenario has assumed that the IWW sector is involved in the EU emissions trading system (EU ETS) from 2030. The ETS is used in Europe for the payment for emissions. Via the European ETS system, 450 large emitters in the Netherlands (mostly factories and power plants) and other emitters in Europe pay for CO_2. They can sell the rights for emissions to each other to achieve a trading market (EC, n.d.$_b$). Currently, this does not affect transportation companies.

The ETS price is included in the BasGoed model for IWW in the high scenarios by increasing the distance costs price with the ETS system price. In this case it is assumed that in 2030 the ETS system price would be $40.6 and in 2050 the price is $162.4 (with a dollar exchange rate of 1.33). Next to that, it is assumed that the CO_2 emissions in the high scenario are 30 g/tkm. Using these assumptions, the price increase per vehicle per kilometre is calculated.

Concluding, the BasGoed model currently does not take into account emissions for the different modes. Therefore, to be able to assess the sustainability of the transportation system using the BasGoed model, adjustments are needed. First, the introduction of the alternative fuels is explained, followed by an introduction of the carbon price to the modal split module.

4.4.1 Introducing the range for alternative fuels to the BasGoed modal split module

To assess the influence of alternative fuels on the sustainability of the transportation system, the outcome of the TCO model is introduced to the modal split module of BasGoed. When the mileage per year where the AFVs are chosen is determined, this number has to be converted to the distances between the OD-pairs in BasGoed. To be able to convert the mileage per year to the distances between the OD-pairs, the following assumptions are made:

- The average speed is 55 km/h (VKM, 2010).
- The loading time is 1.2 hours and the unloading time is 1 hour (VKM, 2010).
- The trucks are active for 9 + 1.2 (loading) +1 (unloading) = 11.2 hours per day (the maximum allowed time for a driver is 9 hours).
- The trucks drive for 261 days per year; based on the average amount of days a driver works (Panteia, 2019).

This results in the following relationship between the OD-pair distances in BasGoed and the mileages per year:

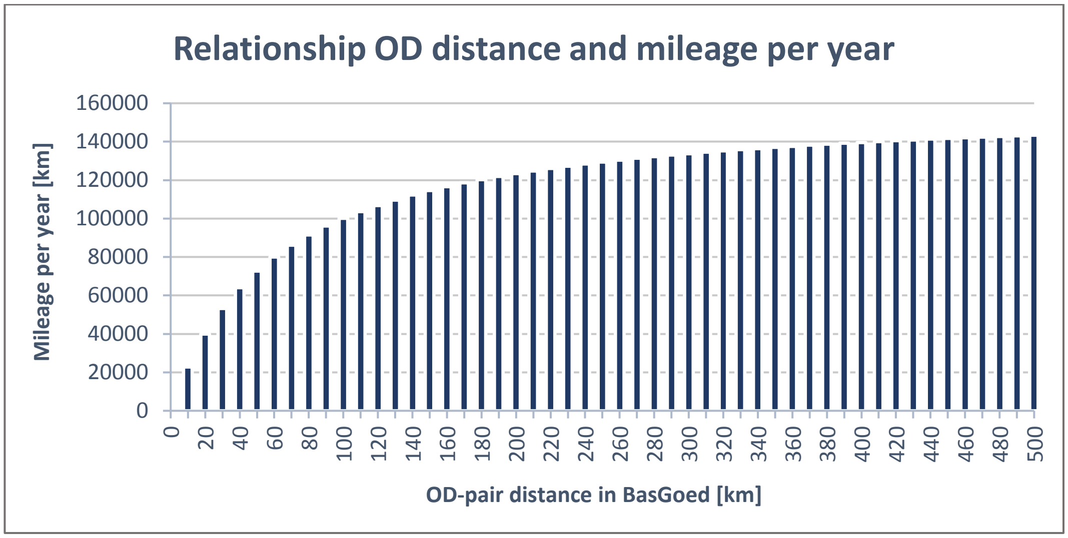

Figure 4.6: The relationship between the distances between the OD-pairs in BasGoed to the mileage per year [km]

Using this relationship, the OD distances in the BasGoed model are linked to the outcome of the TCO model. Within the BasGoed model, it is assumed that 100% of the vehicles switch to BEVs if the OD pair is within the distance range where BEVs are cheaper than diesel vehicles. This results in a difference of the emissions of road transportation within the range. Therefore, a price differentiation of the carbon tax per distance range occurs. It is assumed that apart from the differentiation in carbon pricing, there is no difference between the distance costs of the road mode using diesel and the road mode using BEVs.

4.4.2 Adding the emissions costs to the distance related costs in the modal split module

To add the emissions to the model, the costs of the emissions are added to the distance related costs. To be able to add the costs to the distance related costs, the emissions cost per vehicle kilometre [€/km] is determined. This is done by using the following formula:

Emissions cost rate: $e_v^x \cdot x$ *(Eq. 12)*

With

e_v^x : Emissions per vehicle kilometre at carbon price x [ton CO_2/km]

x : The carbon price [€/ton CO_2]

The variable e_v^x refers to the emissions per vehicle kilometre and differs per mode and the variable x refers to the carbon price which is varied as an input (see chapter 3.1). When the emissions cost rate is known, this is added to the distance related cost in the costs formula: T (see equations 5, 6 and 7). This results in an increase of the costs per vehicle kilometre with the emissions cost rate.

To be able to add the emissions to the BasGoed modal split module, an average of the emissions per mode is needed. However, the exact emissions per vehicle kilometre are difficult to determine as there is a difference in the emissions per vehicle type (shown in chapter 2.4). Figure 4.7 shows the representative emissions per tkm and their ranges per mode type.

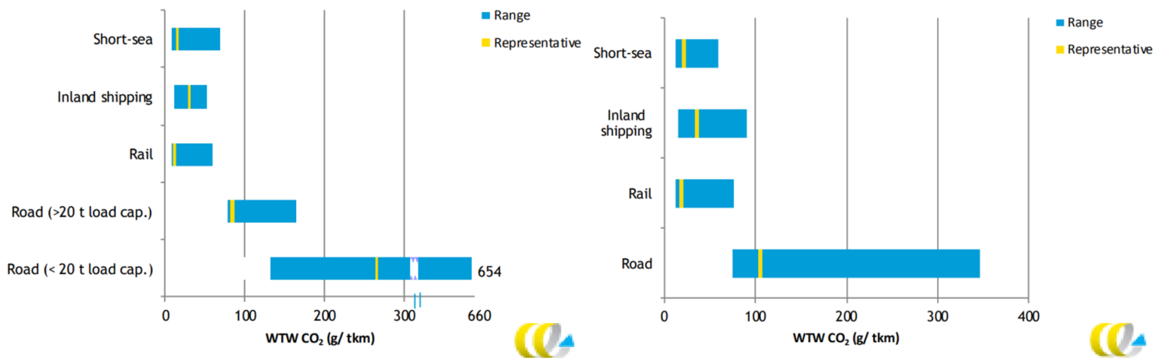

Figure 4.7: Representative WTW emissions per mode, left: bulk/packaged goods, right: containers (CE Delft, 2017a)

To be able to add the costs to the distance related costs, the emissions per vehicle kilometre are needed. Therefore, the emissions per tkm are multiplied by the load factor and the percentage loaded vehicles of the base year (2014) to come to the current emissions per vehicle kilometre:

e_v = e_t * Load factor * Percentage loaded vehicles *(Eq. 13)*

e_v : Emissions per vehicle kilometre [ton CO_2/km]

e_t : Emissions per ton kilometre [ton CO_2/tkm]

4.4.2.1 Emissions caused by unimodal freight transportation

For unimodal transportation, only one emissions cost rate is required. However, a difference should be made between the road transportation using diesel and the BEVs.

4.4.2.1.1 Emissions caused by road freight transportation using diesel

The range for emissions caused by road freight transportation is large as many different vehicle types are available for road freight transportation. CE Delft (2017a) has taken the medium-weight trucks as representative for lighter freight and the tractor-semitrailer as representative for the heavy freight transportation. In 2017, the share of tkm with a load capacity >20t was 98,1% (Eurostat, n.d.) while according to BasGoed, the share of containers in 2014 for road transport was 6.8%. Table 4.12 shows the representative emissions and its shares. This results in a representative emission of 86.49 g/tkm.

Type of freight	CO_2 emissions [g/tkm]	Share of total bulk transport [%]	Share of full transport [%]
Light freight bulk	259	1.9%	93.2%
Heavy freight bulk	82	98.1%	
Container	102		6.8%

Table 4.12: Representative emissions factors and their shares (CE Delft, 2017a; Eurostat, n.d.; BasGoed)

Equation 13 is used to convert this to the representative emissions per vehicle km. The load factor and percentage loaded vehicles of the year 2014 for the road mode are 17.16 and 0.69 respectively. This results in an emission level of 1024.08 per vehicle kilometre. To determine the emissions per ton kilometre for other scenarios, the load factor and percentage loaded vehicles of those scenarios is used (see Table 4.9). The results are shown in Table 4.13.

Scenario	Emissions per vehicle kilometre [g]	Emissions per ton kilometre [g]
Low 2030	1024.08	85.07
High 2030	1024.08	83.77
Low 2050	1024.08	83.77
High 2050	1024.08	81.07

Table 4.13: Emissions per tkm for road transport using diesel per scenario

However, the emissions for road freight transportation are expected to decrease when the carbon price increases (explained in chapter 3.2.1), which results in the following emissions per carbon price level:

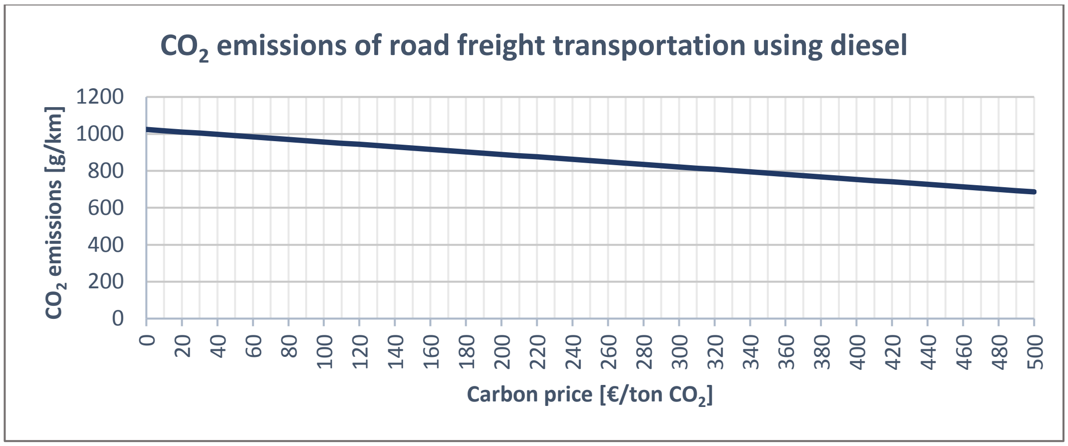

Figure 4.8: The CO_2 emissions per vehicle kilometre of using diesel as fuel for road transport per carbon price

4.4.2.1.2 Emissions caused by road freight transportation using electricity

The amount of CO_2 per tkm differs per type of fuel. Table 4.14 shows the indices that CE Delft (2017_a) created for the WTW emissions of the use of electricity compared to diesel for road freight transportation. According to de Vrijer & Akkerman (2019), the emissions of electricity are 30% to 50% lower compared to diesel vehicles in the current Dutch energy mix.

	Vans	Medium-weight trucks (10-20 GVW)	Heavy tractor-semitrailer
Diesel, Euro V	100	100	100
Electricity	74	79	-

Table 4.14: Indices of WTW emissions for the use of electricity compared to the use of Diesel for road freight transportation (CE Delft, 2017_a)

When the assumption is made that the emissions of energy are currently 75% of the diesel emissions (an average of CE Delft (2017_a) and the 30% of De Vrijer & Akkerman (2019)), the current emissions are set to 64.87 g/tkm. When this is converted to emissions per vehicle by using the same factors as for road transport using diesel, the emissions per vehicle result in 768.09 g CO_2 per vehicle kilometre. The emissions per ton kilometre that result from the difference in percentage loaded vehicles and the load factors are shown in Table 4.15.

Scenario	Emissions per vehicle kilometre [g]	Emissions per ton kilometre [g]
Low 2030	768.09	63.81
High 2030	768.09	62.83
Low 2050	768.09	62.83
High 2050	768.09	60.80

Table 4.15: CO_2 Emissions per tkm for road transport using electricity per scenario

For the use of electricity, the fuelswitch-effect has to be taken into account; the emissions will decrease when the carbon price increases (explained in chapter 3.2.2). The result of the fuelswitch-effect on the emissions per vehicle kilometre is shown in Figure 4.9.

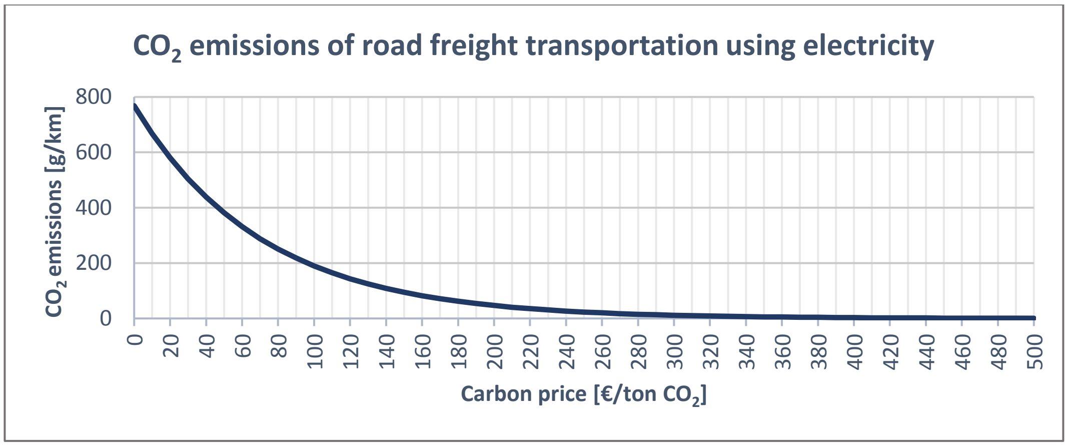

Figure 4.9: The CO_2 emissions per vehicle kilometre of using electricity as fuel for road transport per carbon price

4.4.2.2 Emissions caused by multimodal freight transportation

For multimodal transportation, the emissions of the road mode are also important as the drayage part of the route is performed by trucks. Therefore, the full costs of the emissions per vehicle for transporting freight using multimodal transportation are:

$$e^{x}_{v,road} \cdot x \cdot d_{acc} + e^{x}_{v} \cdot x \cdot d_{itr} + e^{x}_{v,road} \cdot x \cdot d_{egr} \qquad \text{(Eq. 14)}$$

For NSTR 2, 3 and 4 the access and egress is not taken into account and for NSTR 6 the egress distance is not considered (see paragraph 4.3.2.1.2). The emissions of the road freight transportation have been explained above. The emissions for IWW and rail are explained next.

4.4.2.2.1 Emissions caused by IWW freight transportation

To determine the representative emissions for IWW freight transportation (inland shipping in Figure 4.7), CE Delft (2017_a) has taken the average of the Rhine-Herne canal and the Large Rhine vessel. This results in a representative emission of 29.6 g/tkm for bulk and 34.0 g/tkm for container freight transportation respectively. According to BasGoed, the share of containers in the IWW freight transportation was 2.4% in 2014. This results in a representative emission for the mode IWW of 29.61 g/tkm.

Equation 13 is used for the conversion to emissions per vehicle in the base year. The load factor of 2530.31 and the percentage loaded vehicles of 0.66 are used which results in 49448.84 g CO_2 per vehicle. Table 4.16 shows the results for the emissions per tkm per scenario.

Scenario	Emissions per vehicle kilometre [g]	Emissions per ton kilometre [g]
Low 2030	49448.84	29.11
High 2030	49448.84	28.63
Low 2050	49448.84	28.63
High 2050	49448.84	28.63

Table 4.16: CO_2 Emissions per tkm for IWW transport per scenario

However, just like with road transport using diesel, the decrease of emissions when the carbon price is introduced has to be taken into account (explained in chapter 3.2.1). This leads to a decrease in emissions when the carbon price increases (see Figure 4.10).

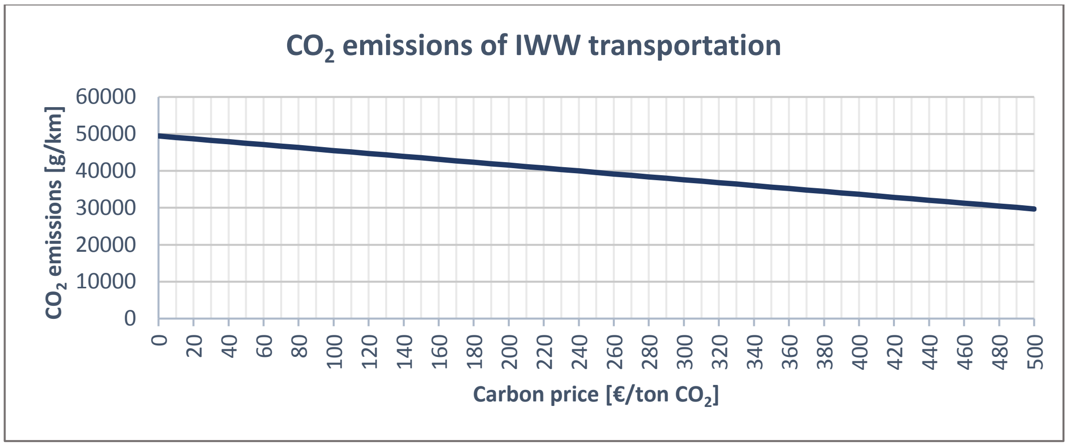

Figure 4.10: The CO_2 emissions per vehicle kilometre of IWW transportation

4.4.2.2.2 Emissions caused by rail freight transportation

As Figure 4.7 shows, the rail mode has the lowest representative emissions. CE Delft (2017_a) has made the assumption that 20% of the trains is powered by diesel and 80% of the trains is powered by electricity. This results in a representative emission of 11.6 g/tkm for bulk cargo transport and 18.8 g/tkm for container transport. According to the data from BasGoed, the share of container transport was 25.6% in 2014. This results in a representative emission for the mode rail of 13.45 g/tkm.

When the data of the base year 2014 is used to convert this to emissions per vehicle kilometre (a load factor of 1040.38 and a percentage loaded vehicles of 0.67), this results in an emission level per vehicle kilometre of 9370.64. The emissions per ton kilometre per scenario that result from this are shown in Table 4.17.

Scenario	Emissions per vehicle kilometre [g]	Emissions per ton kilometre [g]
Low 2030	9370.64	13.22
High 2030	9370.64	13.00
Low 2050	9370.64	13.00
High 2050	9370.64	12.60

Table 4.17: Emissions per tkm for rail transport per scenario

However, for the rail mode several effects of the carbon price must be considered:

- The fuelswitch-effect that was discussed before (chapter 3.2.2) plays a role in the emissions of rail transportation. The decrease formula that was found for the emissions of the generation of electricity is used for the electricity emissions of rail freight transportation of bulk and container transportation. This leads to a decrease of the emissions of the rail freight transportation using electricity.
- It is assumed that the 20% of rail using diesel switches to electricity due to the increase of the price. The assumption is made that a linear decrease in the amount of trains on diesel occurs with a decrease of 0.3% per increase in the carbon price of €10.
- The decrease of the emissions of diesel engines (discussed in chapter 3.2.1) must be taken into account. This leads to a decrease of the emissions of the rail freight transportation using diesel.

When these effects are taken into account, the following WTW CO_2 emissions per carbon price level were found for rail transportation:

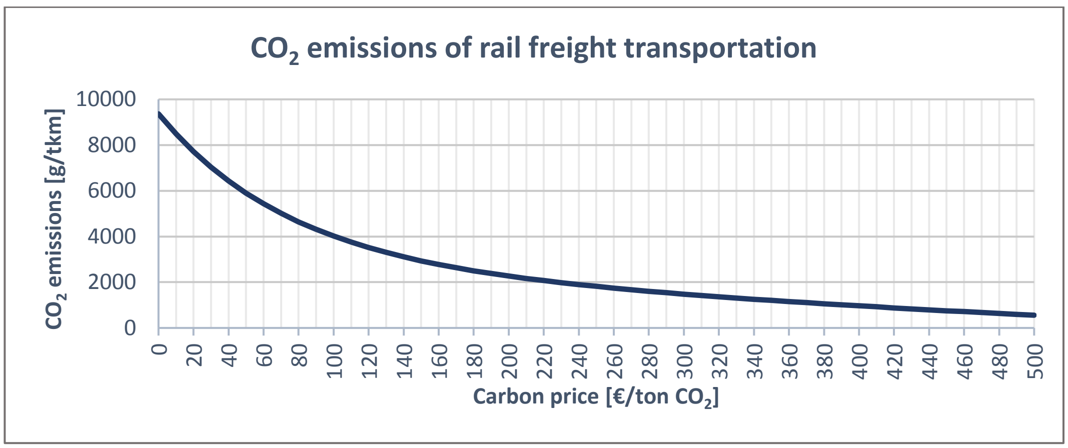

Figure 4.11: WTW CO_2 emissions of rail transportation per carbon price level per scenario

4.4.2.3 The emissions cost rates

As equation 12 shows, the emissions per mode are multiplied by the carbon price to come to the increase in the distance price. The emissions cost rate differs per carbon price level, per mode, per fuel type and per scenario. To be able to illustrate the changes, the emissions cost rates are shown in Figure 4.12. The road mode using diesel has the largest increase, followed by the IWW mode. The rail and road mode using electricity have a smaller increase, in which the fuelswitch-effect clearly shows its effect. The figure shows that the price increases do not differ much per scenario, however, as the original distance prices were different per scenario, the prices compared to the base price do show clear differences. Appendix 0 shows the emissions cost rates compared to the original distance price per scenario per mode.

An important note is that IWW already had a price for emissions (ETS price) implemented in the distance price in the high scenarios. This price is first extracted from the distance price. For the high 2030 scenario this price was €2.9332 per vehicle (€0.0011/ton) and for 2050 this was €11.7328 per vehicle (€0.0045/ton).

Figure 4.12: Increase in price per tkm per carbon price per mode per scenario

4.4.3 Determine the reduction in emissions

When the range where alternative fuels are cheaper and the modal split is determined, the reduction in emissions per tax level can be determined. By multiplying the tkm per mode with the corresponding variable e_t^x (the amount of emissions per ton kilometre at carbon price x), the amount of emissions is determined. A distinction is made between several categories:

1. Unimodal emissions
   a. Tkm transported by road using diesel as fuel
   b. Tkm transported by the road mode using BEVs
2. Multimodal emissions
   a. Tkm transported by IWW
   b. Tkm transported by rail
   c. Tkm transported by road using diesel as fuel to access the IWW and rail service stations
   d. Tkm transported by road using BEVs to access the IWW and rail service stations

5 Results

Chapter 4 has described the adjustments that were made to the models to introduce the carbon price. This chapter gives the results of the analysis. First, the outcome of the TCO model is given, followed by the resulting shift between the transportation modes. Chapter 5.3 gives the reduction in emissions that could be achieved. Thereafter, the total system costs are discussed. The chapter ends with a summary of the sensitivity analysis.

5.1 Range of electric vehicles

The TCO model was used to determine the range where electric vehicles are cheaper than diesel vehicles per carbon tax level. The mileage per year, together with the carbon price, was used as input to come to this range. When the mileage per year increases, the chance that the electric truck becomes cheaper increases as the investments can be shared over more kilometres. Therefore, the larger distances become cheaper first. As the maximum range of BEVs was determined to be 150 km, this distance becomes cheaper first, followed by the smaller distances. The range is shown in Figure 5.1, where the area shows the range where electric vehicles are cheaper than diesel vehicles.

The range for the use of BEVs is the same for every scenario. The figure shows that from a carbon price of €330 the electric vehicles start to gain ground. When the price increases, also smaller distances are served by BEVs with 80 to 150 km as the largest possible distance range at a price of €500.

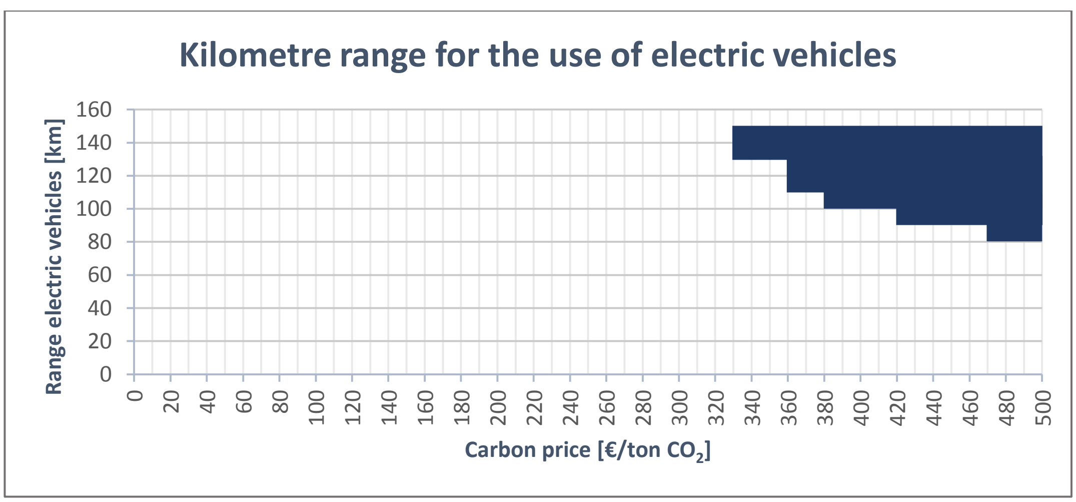

Figure 5.1: Kilometre range for the use of electric vehicles per Carbon price level

Initially, this study also researched the possibility to use a hydrogen fuel cell vehicle (HFCV). However, it was found that the HFCV is not economically viable in the given range for the carbon price. The performed analysis for the HFCV is explained in appendix E.

5.2 CHOICE OF MODES

The carbon tax influences the choice of mode because of the difference in price. The effect of the carbon price on the shift between modes is explained here.

5.2.1 Modal split in tonnes

Appendix G shows the total modal split of all the freight that is transported (BEVs count as road). Only little changes in the modal split. The share of the road decreases until the point that electric vehicles are introduced, the share then starts to increase again. However, this change is within 2 percentage points. The share of IWW increases until the point that BEVs are introduced, after which the share start to decrease again. The share of rail increases when the carbon price increases with a maximum of 0.24 – 0.31 percentage-points, differing per scenario. From these shares it can be concluded that the decreasing share from the road mode shifts mostly to the IWW mode and when BEVs are introduced, a shift occurs from IWW to road.

5.2.2 Modal shift per distance class per tax level

While the modal split in tonnes does not change much, a clear shift between the modes is seen per distance class. Figure 5.2 shows the modal shift per distance class for the high 2030 scenario at a carbon price of €200 per ton CO_2 while Figure 5.3 shows the modal shift per distance class for the high 2030 scenario at a carbon price of €400 per ton CO_2. The figures show the percentage of tons that shift from road to IWW or rail transportation. The distance classes are based on the distances for road transport. Figure 5.2 show that at a carbon price of €200, the tons shift from road transportation to rail and IWW, with the larger distances shifting more towards the multimodal modes and more shifting towards IWW than to rail. The larger shift to IWW than to rail can partly be explained by the fact that rail transportation is not available in most zones, resulting in no possibility to shift towards rail. IWW has a larger availability, resulting in a larger shift.

Figure 5.3 shows that when a price of €400 is introduced, which makes road freight transportation switch to BEVs within a range of 100 to 150 km, a reverse modal shift appears within the BEV range. The largest shift within this range is the shift from IWW to road. Outside of the range, the modal shift from road towards multimodal transport continues with a larger impact.

Next to the shift per distance class, Figure 5.2 and Figure 5.3 also show the share of the total tonnes that are transported by road. 67% of the freight transportation that is transported by road is within the distance range of 100 km. Therefore, the big shift that can be identified for the large distance classes come from a small share of the total freight transport. This explains the big shift that can be seen per distance class but the small shift in the total modal split in tonnes. Appendix H shows the shifts per scenario and per carbon prices of €100, €200, €300, €400 and €500.

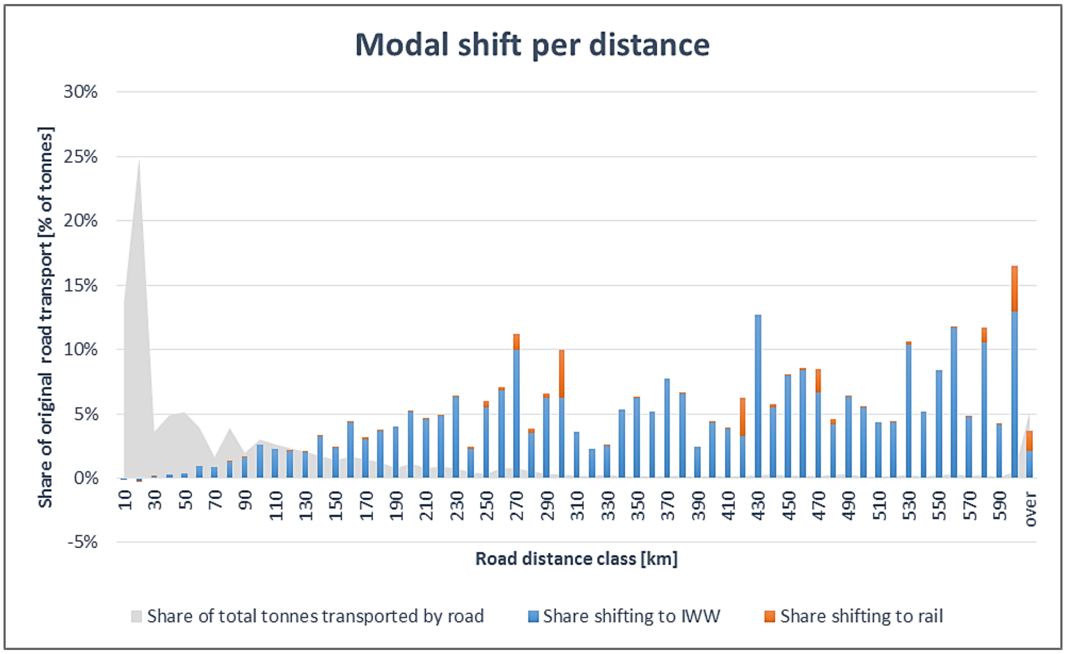

Figure 5.2: Modal shift per distance class of the H2030 scenario at a carbon price of €200/ton CO_2

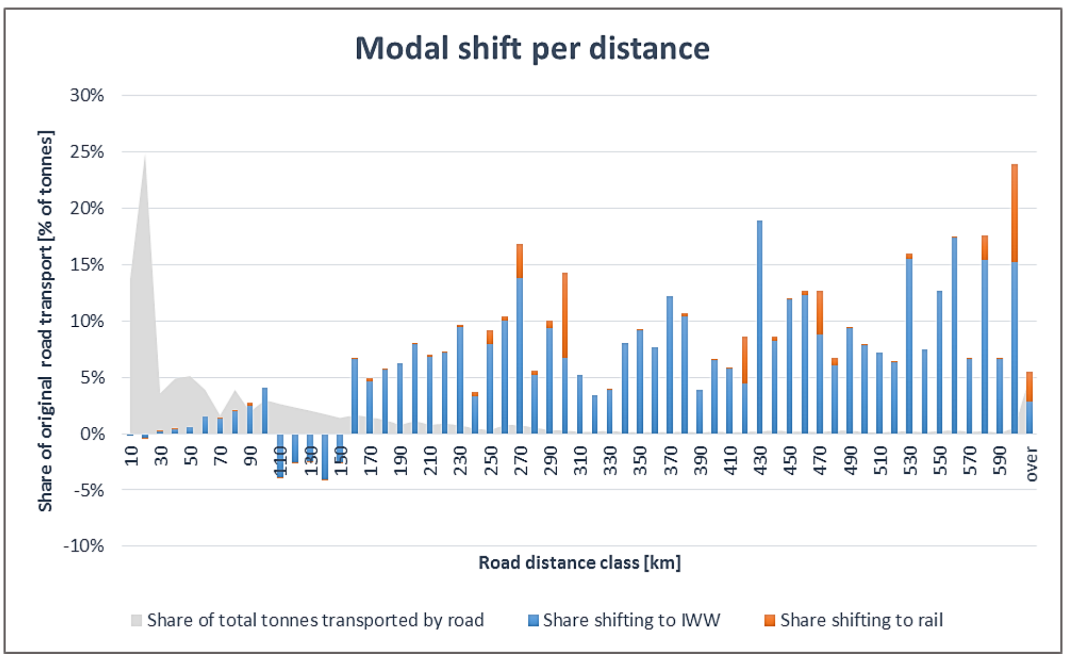

Figure 5.3: Modal shift per distance class of the H2030 scenario at a carbon price of €400/ton CO_2

5.2.3 Modal split of the tkm

As was explained in the last paragraph, the modal split in tonnes is not affected much by the introduction of the carbon price. However, a modal shift appears in different distance classes. To be able to show this effect, the modal split in tkm is shown in Figure 5.4. The figure shows the percentage of the amount of ton kilometres that is transported per mode per carbon price level. The figure shows that the amount of tkm of road transport using diesel is slowly decreasing, until the point that BEVs are introduced. At this point the decrease of road transport slows down.

For the rail and IWW mode, an increase of their shares takes place. The share of IWW increases the most with 1.46 – 1.8 percentage points. The share of rail increases with 0.91 - 1.11 percentage points, which is different per scenario. Furthermore, the figure shows that BEVs are not used for the road transportation that is used to access service station for the IWW and rail mode as the BEV range does not reach these distances. However, due to the shift to IWW and rail, more access transportation is needed, resulting in a slight increase of the share of access transportation by the road mode using diesel.

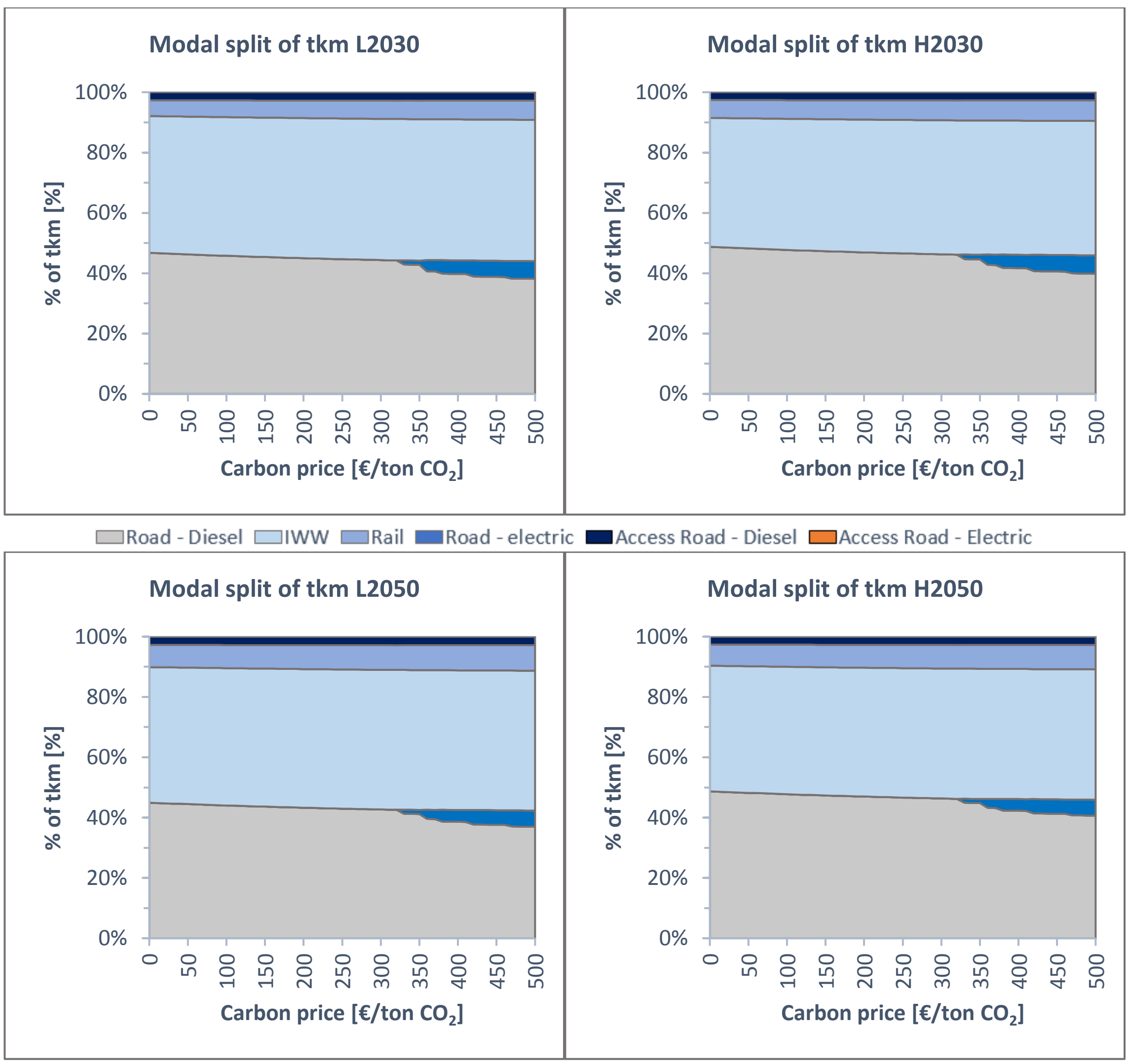

Figure 5.4: Percentage of tkm transported per mode per carbon price level per scenario

5.3 REDUCTION IN EMISSIONS

Figure 5.5 shows the reduction in emissions compared to the Basgoed findings without carbon tax per scenario. The scenarios show the same course of the line. The emissions decrease gradually with the introduction of the BEV ranges resulting in an accelerated decrease. For the Low 2030 scenario, the reduction can lead to a maximum of 43.20% at a price of €500 while at the high 2030 scenario the maximum reduction can be 43.10%. For the low 2050 scenario, a carbon price of €500 can lead to a maximum reduction of 43.18% while the high 2050 scenario can lead to a reduction of 43.22%. Note that at a carbon price of 0, the high scenarios already lead to a reduction in emissions due to the ETS price that was reduced from the IWW distance price.

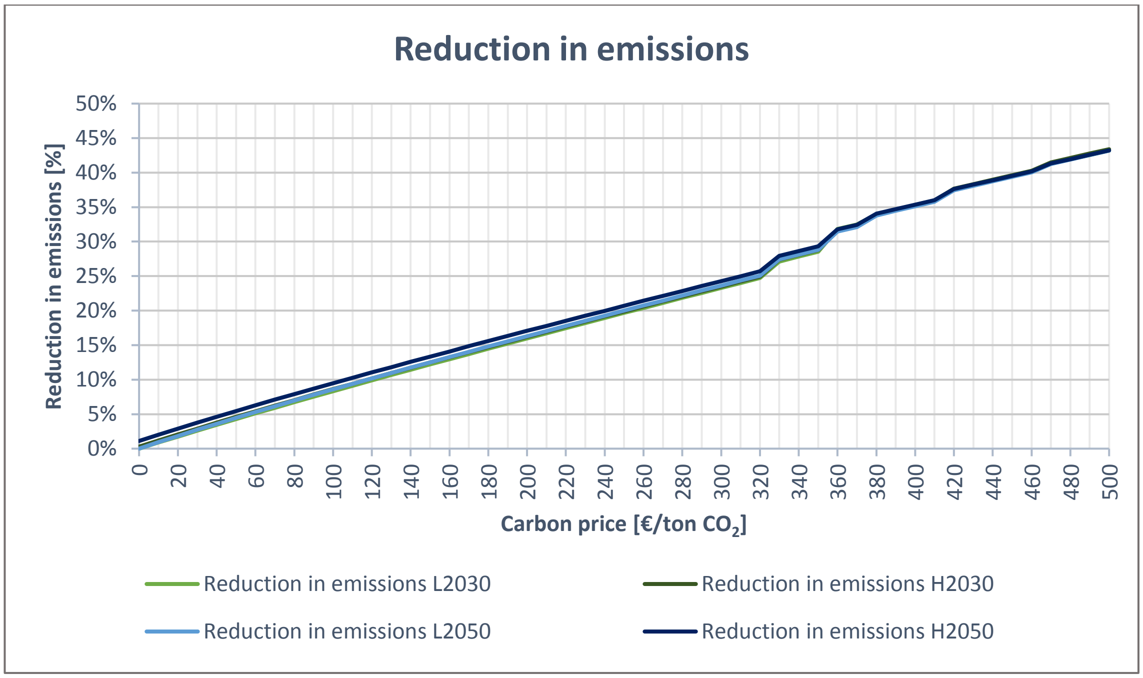

Figure 5.5: The reduction in emissions per scenario per carbon price level

5.3.1 Reduction in emissions together with the modal split in tkm

Figure 5.6 shows the reduction in emissions together with the modal split in tkm per carbon price level per scenario. As shown, a gradual decrease of the emissions takes place until a carbon price of €330, from which BEVs start playing a role. The increasing share of tkm of the BEVs is clearly visible in the decrease. However, the shifts between the modes do not show a clear relationship with the decrease in emissions.

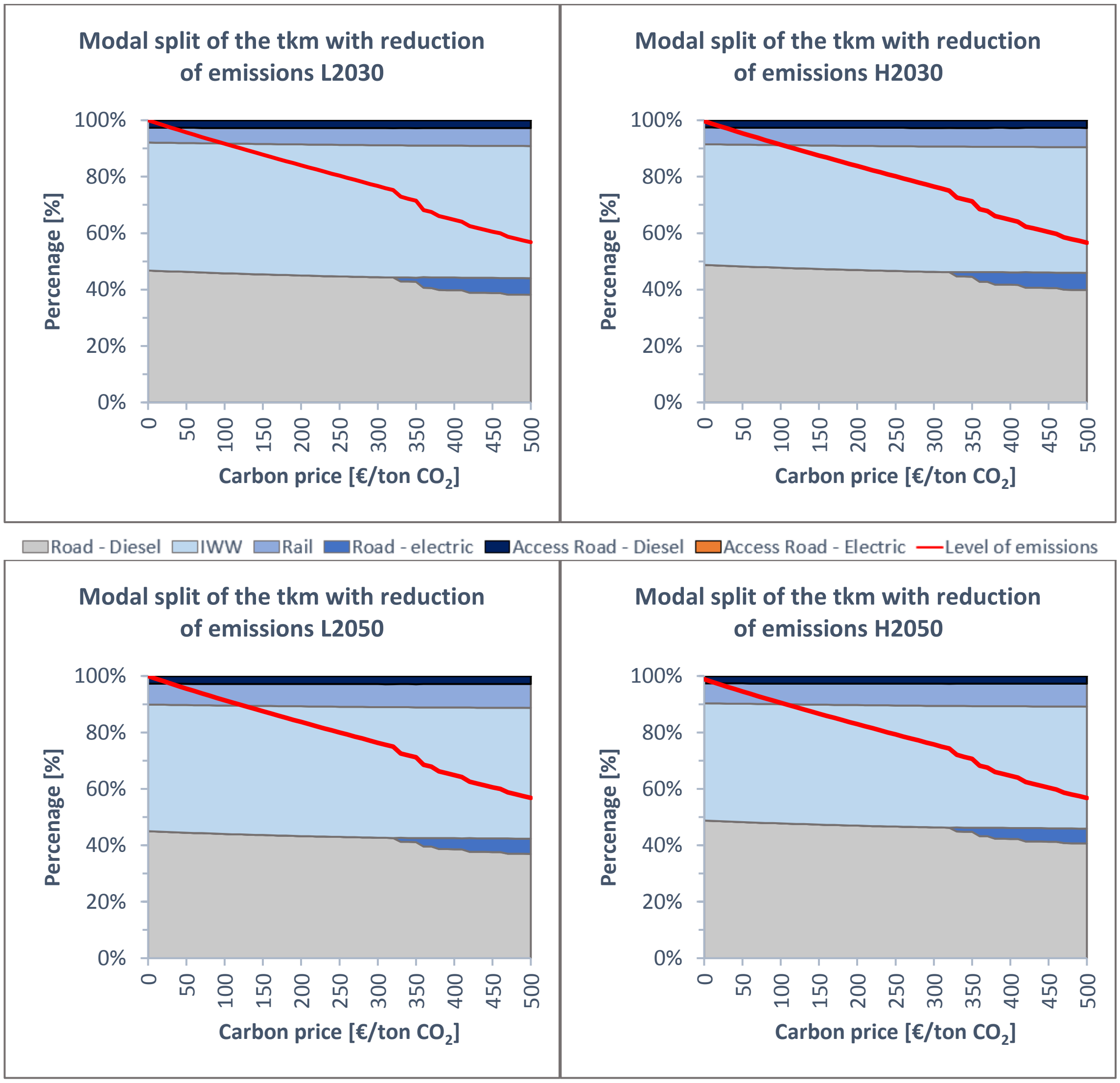

Figure 5.6: The modal split in tkm with reduction of emissions per carbon price level per scenario

5.4 Total system cost

When the carbon tax is introduced, the cost of the system will increase. The total system costs are calculated using equation 5 (the cost formula from BasGoed) which considers the (un)loading costs, the time costs and the distance costs. These differ per scenario and per carbon price level. The full price structure and the course of the costs is shown per scenario in appendix I.

Figure 5.7 gives an overview of the total system cost compared to the reduction in emissions. The total system cost increases gradually with a maximum value of between 16.5% and 18.1% at a price of €500. When BEVs are introduced to the system, no increase in the total system cost is shown while the course of the emissions shows an accelerated decrease. Therefore, the introduction of BEVs can be considered as a cost-efficient solution to decrease the emissions.

When looking at the total system cost without carbon prices, a decrease is shown (with a maximum value between 1.9% and 2.0%). Note that the utility function of the BasGoed model takes into account several other factors that are not directly tied to costs. The carbon tax results in that the other factors that made transport planners initially choose for the road mode are compensated by the increasing cost of the road mode. This causes a shift towards cheaper modes (e.g. rail and IWW) which makes the transportation system more cost-efficient. However, this cannot compensate for the increase in the distance costs by the taxes. Therefore, the total increase in the system price is solely caused by the carbon tax that must be paid.

Next to the percentage increase of the costs, Figure 5.7 shows the carbon tax revenues per carbon tax level per scenario using the bar chart (from left to right: L2030, H2030, L2050 and H2050). The revenue by the carbon tax differs much per scenario. This is mainly due to the fact that in the high and 2050 scenarios an increase in the amount of freight to be transported is expected, resulting in a higher tax. The revenues differ in the range of 0 - 6.3 billion euros.

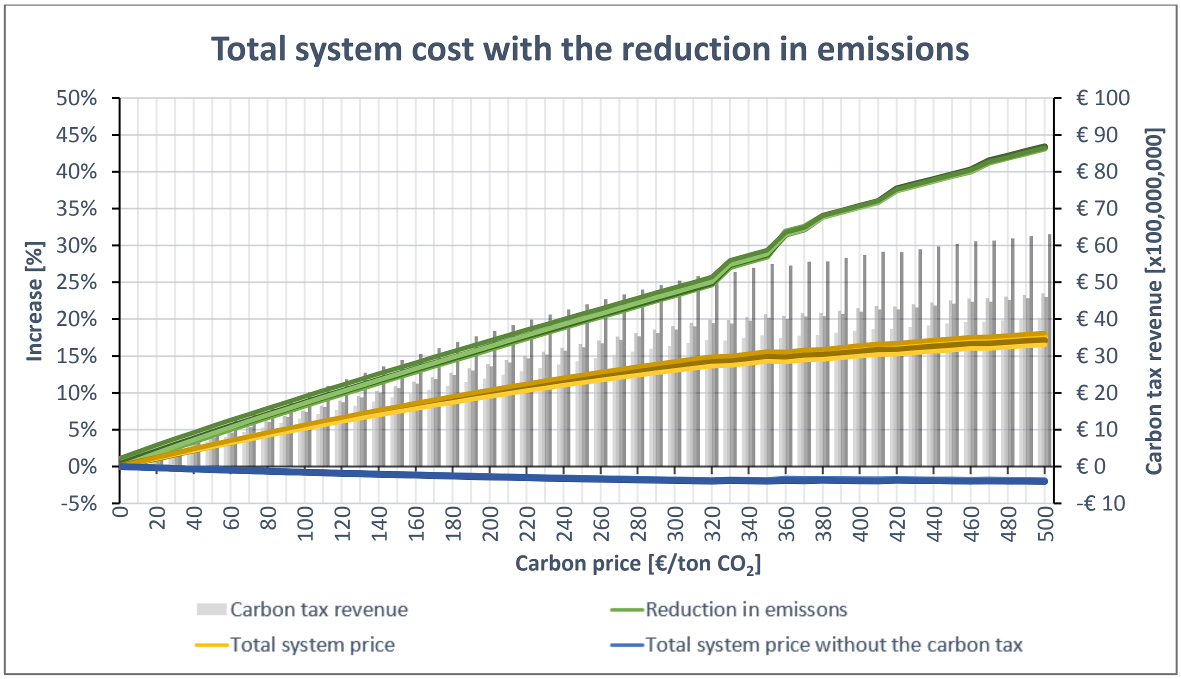

Figure 5.7: Increase in total system cost with the reduction of emissions

5.5 Sensitivity analysis

A sensitivity analysis is performed to research the influences of the assumptions and uncertainties on the reduction in emissions. The analysis is performed on one scenario (the high 2050 scenario) as the results have shown that the scenarios react the same to the different factors. Appendix J shows the full analysis with the sensitivity to the changes per carbon tax level. A summary of the results of the analysis is shown in Table 5.1.

First, the sensitivity to the energy generation market is researched; the effect of the carbon tax on the increasing technology of the conventional diesel vehicles and the fuelswitch-effect. It was found that the reduction in emissions is very sensitive to the change in the decrease rate; when the emissions are 50% less sensitive to the introduced carbon price, the reduction in emissions also decreases with 50%. However, when the decrease rate is increased with 50%, the change of the total reduction increases with 28% in the High 2050 scenario.

Note that the different decrease rates result in different outcomes of the TCO model. Therefore, the course of the reduction in emissions differs (see appendix J).

Second, the maximum range of BEVs was varied. The maximum range of 150 km was increased and decreased with 20 and 50 km. It was found that a decrease of 50 km leads to 8.6% decrease of the reduction while a maximum range of 50 km would lead to an increase of 7.7% compared to the original reduction in emissions at a carbon price of €500. Furthermore, the maximum range of BEVs also has an impact on when BEVs become economically viable. When the maximum range increases the BEVs become an attractive option at a cheaper carbon price (see appendix J).

Third, the emissions per mode were varied. In this case, the current emissions of the modes were increased and decreased with 10% and 30%. The reduction in emissions due to the influence on the energy generation market stays the same. The variations in the emissions of the modes result in different BEV ranges per carbon price (see appendix J). When the emissions per mode increase with 30%, BEVs become cheaper at a lower carbon price and the maximum range at €500 is 50-150 km. This enables a part of the access transportation to be transported by BEVs and a further reduction in emissions.

When the emissions are 30% less than determined, the relative change of reduction is almost -13%. This can be explained by the fact that the difference in emissions is smaller so shifting to another mode is less rewarded. Next to that, BEVs do not become a cheaper option at all due to the smaller difference in emissions between conventional diesel vehicles and BEVs.

	Change	Reduction in emissions at a price of €500	Relative change of reduction in emissions at a price of €500
Original		43.22%	
Emission decrease rate	-50%	21.19%	-50.97%
	-20%	34.58%	-20.00%
	+20%	48.84%	13.00%
	+50%	55.41%	28.21%
Maximum BEV range	-50km	39.51%	-8.59%
	-20km	41.88%	-3.10%
	+20km	44.78%	3.60%
	+50km	46.56%	7.73%
Mode emissions	-30%	37.66%	-12.87%
	-10%	42.58%	-1.49%
	+10%	44.18%	2.22%
	+30%	45.98%	6.38%

Table 5.1: Results of the sensitivity analysis

6 DISCUSSION AND CONCLUSION

This chapter first presents a discussion of the study. Thereafter, the conclusions and recommendations for further research are given.

6.1 DISCUSSION

First, the methodology is discussed which focuses on the models that are used and the assumptions that are made. Thereafter, the results of the study are discussed.

6.1.1 Methodology

The influence of the carbon price on three areas is researched. First of all, the introduction of a carbon price on the reduction of emissions of conventional diesel vehicles is assumed. Due to the lack of a relation found in literature, an assumption is made resulting in an uncertainty in the research. However, it is logical to assume the decrease of the emissions as the possible measures are known (Harvey, 2013) but at the moment too expensive. Next to that, the fuelswitch-effect is determined by extrapolating the study of Levin et al. (2019). By the extrapolation another uncertainty is introduced. However, as the renewable energy is at the moment available but expensive, a switch to more renewable energy is logical to expect.

Second, a TCO model is used for the research on when BEVs become an economically viable option. The model is based on an all-or-nothing algorithm which results in the assumption that the decision on using a diesel vehicle or a BEV is solely based on cost minimization. However, Seitz et al. (2015) found that for some transport organizations environmental reasons are more important than the cost-efficiency in the adoption of CO_2 saving technologies. This might delay or accelerate the switch to BEVs. Furthermore, for simplification reasons, the vehicle type truck trailer was chosen to research. However, the costs per vehicle type differ much. To be able to come to a more detailed research, a more disaggregate model should be used. For this study, on an aggregate level, these simplifications are needed in order to come to the results.

Third, the modal split module of the BasGoed model is used. By using only the modal split module and introducing the outcome of the distribution module as an input, the influence of the changing parameters on the distribution of the freight is neglected. This results in that the possible economic impact is not taken into account in the study, which could be significant. Next to that, the distance price excluding carbon tax of road using diesel and road using electricity has been kept the same in the BasGoed model. In reality, the prices will differ as fuel prices and maintenance to the trucks differ.

This study has focused on the three areas explained above. However, the carbon price can influence many other fields. For example: extra infrastructure investments might be done and changes in the economy might occur. These fields could in their turn be an influence to the results that were found in this research.

6.1.2 Results

It is important to mention that these results should not be interpreted as what would happen in the future. Rather, the results of this study give an idea of what the effects of carbon pricing could be and how this is related to the CO_2 emissions of the freight transportation in the Netherlands.

The result of the TCO model shows that currently the truck-trailer BEVs are not economically viable, which is in line with the current literature. When the carbon price increases, the BEVs become cheaper than conventional diesel vehicles for the larger distance ranges, which is supported by the common hypothesis that an "EV will become relatively more competitive compared to a conventional diesel vehicle with an increasing mileage" (Taefi et al., 2017) and with an increasing mileage the carbon pricing becomes more effective as well (Arroyo et al., 2019). However, as the model focuses on costs only, other factors like environmental zones are not taken into account. This could lead to a different shift to BEVs.

The results of the BasGoed model show that the choice of modes is not influenced much by the introduced carbon price. This is in line with Blinge (2014), who states that the freight transport system is very robust, resulting in no drastic changes due to a CO_2 tax. However, other studies focusing on the container freight transport in the Netherlands found a larger shift between the modes (Zhang et al., 2014; Zhang et al., 2015). This study shows that when other commodities are also considered, this large shift does not take place. Next to the little sensitivity to the cost changes, this small shift can be explained by the fact that for many zones in BasGoed there is no availability for IWW or rail. This results in no possibility to shift to other modes.

The resulting reduction in emissions increases gradually. When the carbon price increases, the CO_2 emissions decrease further (as expected). The decrease is mainly caused by the increase in the efficiency of the conventional diesel vehicles (as the sensitivity analysis shows). When the BEVs are introduced, an accelerated decrease takes place. This is in line with current literature stating that alternative fuels are the most effective way for the reduction in emissions (Chen et al., 2018). However, the total system cost increases as well. This can decrease the demand for freight transportation (Beuthe et al., 2013) which is not considered in this research but can have an impact on the Dutch economy.

6.2 Conclusion

The future of the transportation and energy sectors depend on hardly predictable technological progress, market developments and policy issues. This makes it hard to make predictions about the future. Nonetheless, this study has resulted in some final conclusions. First, the sub questions are answered, followed by the main research question.

RQ. 1. Which transport modes are currently used and what are the current emissions?

Currently, freight is mostly transported using trucks, followed by IWW and rail. The advantage of the road is that the network is the densest which means no transhipment to other modes is needed. This results in a faster transportation and no need of the transhipment costs from one mode to another. When looking at the emissions, the road mode emits the most CO_2 of the three modes. This results in an unsustainable distribution; the transport mode that is used the most is the most unsustainable.

RQ. 2. What shift to alternative fuels can be realized within the Netherlands when looking at the road freight transportation?

This study focuses on the possibility of transportation by BEVs and hydrogen trucks. By introducing a carbon price, the price of fuel for conventional diesel vehicles increases more than the price for BEVs and for HFCVs. By using a TCO model, based on the AON algorithm, the breakeven point where electric vehicles are cheaper than diesel is determined. It was found that at a carbon price of €330 electric trucks become a cheaper alternative within a particular distance range. When the carbon price increases, a larger distance range (from the maximum range of 150 km in the direction of 1 km) becomes available. This results in a shift to the alternative fuel electricity in a particular niche market: at the maximum carbon price of €500 the BEVs are used in the range of 80-150 km. When looking at the modal split of tkm, the BEVs start performing around 1.5% of the total tkm at a price of €330, with an end share of around 6% of the total tkm at a carbon price of €500.

By adding the hydrogen option to the existing TCO model, it was found that hydrogen trucks are too expensive to reach a breakeven point in costs with conventional diesel vehicles. The carbon price must become higher than €500 to be able to make hydrogen trucks a cost-attractive option.

RQ. 3. What modal shift can be realized within the Netherlands when looking at the intermodal transport network?

This study has found that the total modal split in tonnes is not sensitive to the addition of carbon pricing (the differences are within 2 percentage-points). However, when analysing the modal shift in tonnes per distance class, it was found that a modal shift takes place at larger distances. Therefore, the modal split in tkm was researched. This modal split shows a slight reduction of the unsustainable modes; a shift towards more sustainable options. However, when the carbon price reaches a point that makes BEVs a cheaper alternative within certain distance ranges, a reverse modal shift appears within this distance range.

RQ. 4. How can carbon pricing affect the CO_2 emissions of freight transport in the Netherlands, given the transportation modes and energy sources?

Introducing a carbon price affects several areas of freight transport in the Netherlands. First of all, the CO_2 emissions of conventional diesel vehicles will decrease as investing in new reduction technologies is rewarded. Next to that, electric freight vehicles become a price-attractive option for the road mode, resulting in a decrease of emissions of the most unsustainable and most used mode. Furthermore, a slight modal shift occurs in which larger distances switch more to the sustainable modes than smaller distances. However, due to that the effect on the modal split is little, the decrease in CO_2 emissions caused by a modal shift is found to be little.

HOW CAN THE FREIGHT TRANSPORTATION NETWORK USE IN THE NETHERLANDS BECOME MORE SUSTAINABLE, CONSIDERING MODAL SHIFT AND ALTERNATIVE FUELS?

Introducing a CO_2 price was found to be an effective policy for the reduction of CO_2 emissions in the Netherlands. The effect that has the most influence on the reduction in emissions is the improvement of the technologies for the conventional diesel vehicles and the fuelswitch-effect. Next to that, a slight modal shift to more sustainable modes takes place. Furthermore, when the carbon price makes BEVs an economically viable option, this results in a reverse modal shift; using the road becomes cheaper and more attractive. As BEVs have few emissions, this leads to an accelerated decrease of the CO_2 emissions.

However, it should be taken into account that the introduction of a CO_2 price leads to an increase in the total system cost. This increase is only due to the carbon price and not due to the costs of the transportation itself. The impact of the increase in the total system cost is not taken into account in this study, but can result in major changes in the economy.

When looking at the current expectations of the future price of the ETS system, a maximum price of about €100 in 2030 is mentioned. This study shows that this can result in a decrease in CO_2 emissions of around 10%. To be able to reach the climate goals, this decrease will not be enough. Therefore, it can be concluded that in order to reach the climate goals by means of carbon pricing, the carbon price must be significantly higher than the expected price of the ETS system.

6.3 Recommendations

Several recommendations can be offered following this study. First recommendations for policymakers are given, followed by recommendations for the industry and for further research.

6.3.1 Policy

- The reduction in emissions is mostly caused by the decrease in emissions due to the improving technology of conventional diesel vehicles and the introduction of BEVs. The carbon price leads to only a slight shift to more sustainable modes. It is important to promote and invest in the sustainable technologies to reach the reduction in emissions.
- The carbon price leads to alternative fuels being an economically viable option, which causes a reverse modal shift. This can lead to problems like congestion, nuisance and accidents (Sun et al., 2019). Therefore, for the reduction of road vehicles, other policy measures should be considered.
- It is recommended to introduce the carbon price on a European level as the economic position of transportation in the Netherlands is damaged when the price increases. Next to that, introducing a carbon price for IWW might be a problem, as the act of Mannheim does not allow member states to impose any tolls, taxes, duties or charges based on the factor of navigation (IVR, 2018).

6.3.2 Industry

- To decrease the total prices, many reductions are possible by optimizing current vehicles. It is recommended for transportation companies to consider investments in these new technologies. For the car manufacturers an increase in the demand for more sustainable vehicles can be expected when a carbon price is introduced. Therefore, investing and innovating in these vehicles can pay off.

- When a carbon price is introduced, BEVs might become an interesting alternative. It is recommended for transportation companies to research per situation whether BEVs are economically viable as the costs of the vehicles differ per vehicle profile.
- When a carbon price leads to a shift to BEVs, the electricity generation industry should expect an increase of the demand for electricity (Kluschke et al., 2019). Besides that, the demand for renewable energy will increase as well due to the fuelswitch-effect.

6.3.3 Future research

This study has tried to estimate the possible emissions by the transportation of freight by using the information available. Several researches are recommended to be able to improve the estimation:

- This study has not taken into account the economic impact of the carbon price. Higher prices can decrease the demand for freight transportation (Beuthe et al., 2013). Next to that, the carbon tax might enable investments in new infrastructure projects. These changes might strengthen the possible reductions. Further research is recommended to the influence of the increasing price on the production and consumption of the sector and on the influence of possible infrastructure investments.
- Most of the reduction in emissions is caused by the influence of the carbon price on the improvement in technology on conventional diesel vehicles. However, assumptions were made to be able to come to the decrease. Therefore, it is recommended to further research the influence of the different levels of the carbon price on the improvements of technologies of the modes.
- This study has considered the influence on the electricity generation market based on the research by Levin et al. (2019). However, this research is based on the American electricity generation market and researched the influence until a carbon price of $60. To come to a more substantiated estimation, it is recommended to research the influence of the carbon price (with the full range until €500) on the Dutch electricity generation market.
- This study has focused on BEVs and hydrogen trucks as alternatives to road freight transportation. However, Kluschke et al. (2019) found that current literature also mentions other alternative fuels as promising alternatives, like catenary electric vehicles, hybrid electric vehicles and compressed natural gas vehicles. To be able to provide an improved estimation, it is recommended to research the possibilities of other alternative fuels that can become economically viable as well.
- Currently, the maximum BEV range was set to 150 kilometres. However, when battery swapping or opportunity charging is taken into account, this maximum range can be enlarged. It is recommended to research the influence of the enlarged range and the accordingly required waiting times on road freight transportation.

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A. ROAD NETWORK IN THE NETHERLANDS

Figure A.1: Dutch main roads (Staatscourant, 2015)

B. WATERWAYS NETWORK IN THE NETHERLANDS

Figure A.2: Dutch Waterways network (Bureau Voorlichting Binnenvaart, n.d.)

C. RAIL NETWORK IN THE NETHERLANDS

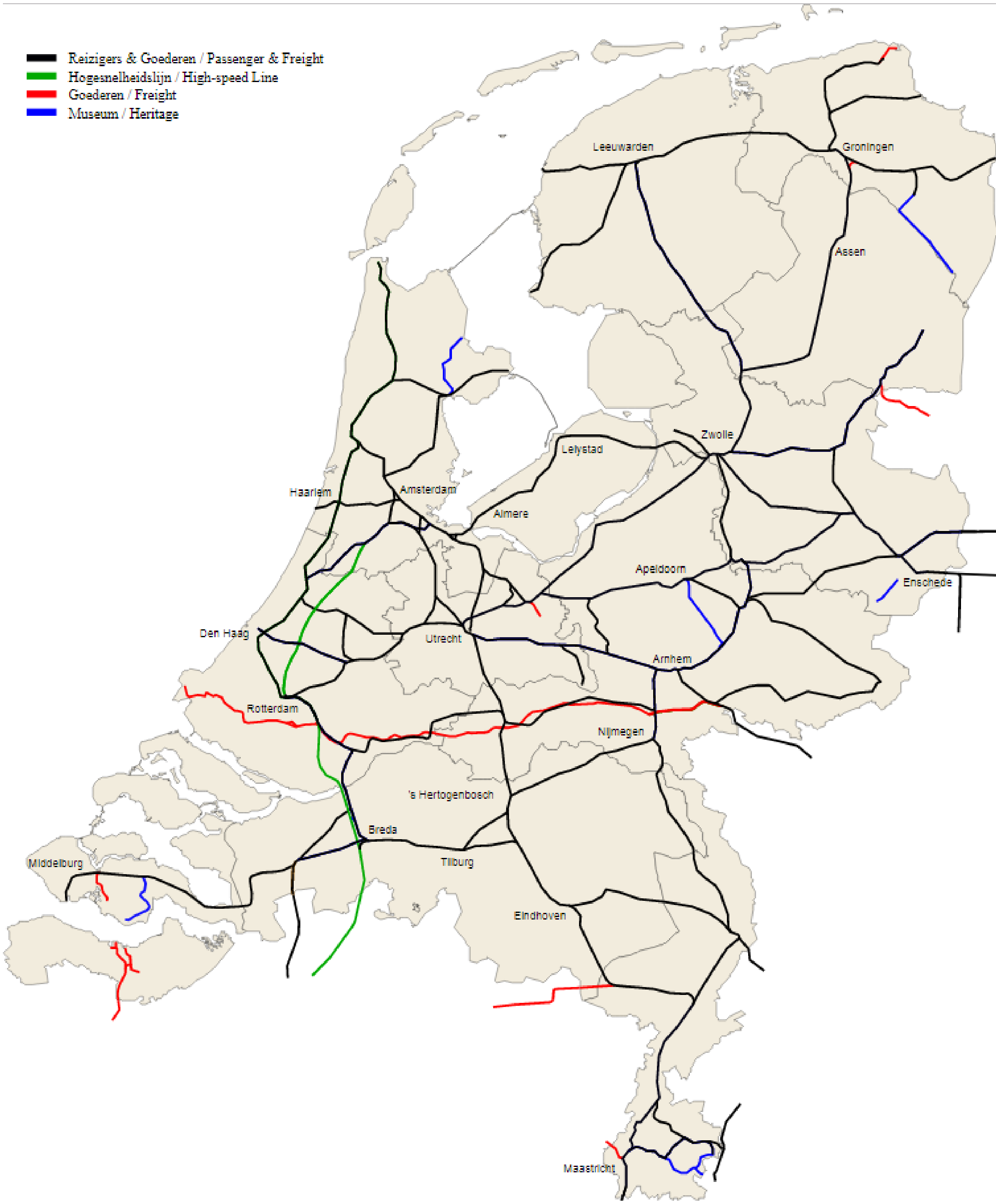

Figure A.3: Railway network in the Netherlands (Wikimedia Commons, 2018)

D. ROUTES NETWORKS IN THE BASGOED MODEL

Figure A.4 shows the connection of the rail network with BasGoed. The Routgoed network is shown in grey and the connections to the COROP zones are illustrated in red.

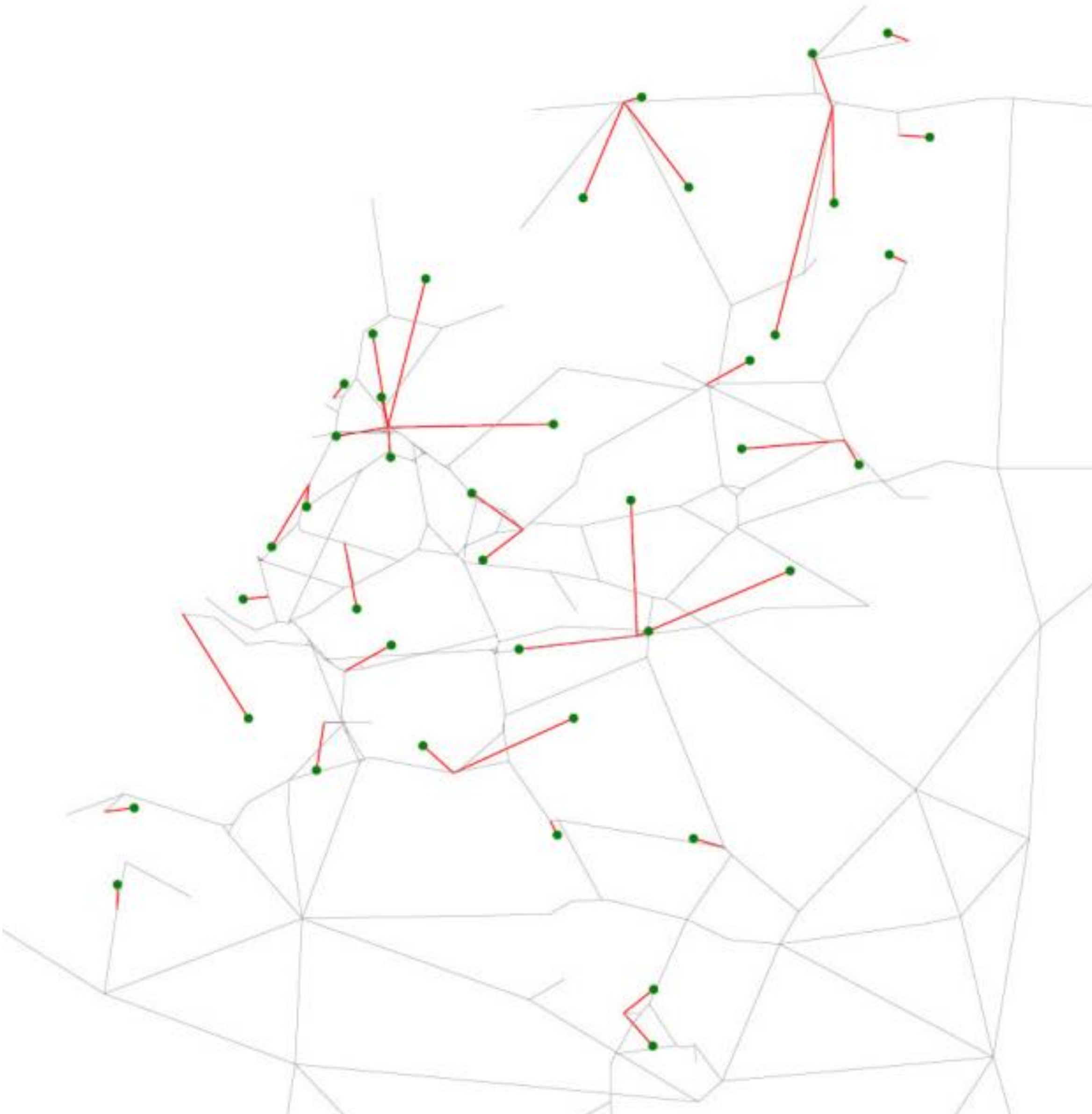

Figure A.4: RoutGoed network with the connections to the COROP zones (de Jong et al., 2010)

Figure A.5 shows the difference between the zones of the BIVAS model and the BasGoed model. The zones that are outlined in red are the COROP zones while the purple zones refer to the zones in BIVAS.

Figure A.5: BIVAS zones and the COROP zones (de Jong et al., 2010)

E. HYDROGEN FUEL CELL VEHICLE ANALYSIS

Initially the alternative fuel hydrogen was planned to be researched as an alternative to the conventional diesel vehicle for road transportation. However, the TCO analysis found that HFCVs would not become an economically viable option when introducing a carbon tax within the price range of €0-€500. To determine when HFCVs are cheaper, the hydrogen option is added to the Panteia TCO model. To be able to perform this analysis, the following factors are taken into account:

Factor	Represents	Value
Fixed cost per year	Vehicle road tax (input)	Same as BEV and diesel
	Toll	Same as BEV and diesel
	Interest (vehicle purchase loan)	Same as BEV
	Insurance	Same as BEV
	Misc. Vehicle costs	Same as BEV and diesel
Variable costs per km	Depreciation costs (vehicle)	**€46,875 per year**
	Depreciation costs(battery)	NA
	Carbon tax	NA
	Tires	Same as BEV and diesel
	Diesel	NA
	Electricity	NA
	Hydrogen	**€0.71 per kilometre**
	Repair/Maintenance	Same as BEV
Special transportation costs	-	Same as BEV and diesel
Private charging system	NA	Not taken into account
Driver costs	Hourly wage, allowances, other costs	Same as BEV and diesel
General costs	Salary costs, building, miscellaneous	Same as BEV and diesel

Table A.1: factors of the TCO analysis of HFCVs

The factors that have the same value for BEVs and diesel vehicles are also used for HFCVs. Next to that, the interest, insurance and repair/maintenance costs of BEVs were adopted as values for the HFCVs. This is a very optimistic scenario as in reality the HFCV trucks are more expensive than BEVs which results in higher interest and insurance costs. The two factors that are changed are the costs of the fuel and the costs of the depreciation. The costs of the fuel for hydrogen are calculated by using a consumption rate of 7.5 kg/ 100km (Roland Berger, 2017) and a price for hydrogen of €10/kg (Janson, 2019). The depreciation costs for the vehicle refer to the costs of the vehicle per year. The TCO model uses a life time for a BEV of 8 years, which is also used for the HFCV. The cost of a truck are assumed to be $375,000 (trucks.com, 2019). When these values are used for the calculation of the price per kilometre and a carbon price of €500 is introduced to diesel vehicles, the hydrogen trucks do not become economically viable.

F. INCREASE IN PRICE/TKM PER MODE FOR EACH SCENARIO

The increase in the price per tkm differ per scenario. Next to that, the distance price was already different when the carbon price had not been introduced yet. The figures below show the original distance prices with the price increase due to a carbon tax per scenario.

Increase in road using diesel price/tkm per scenario

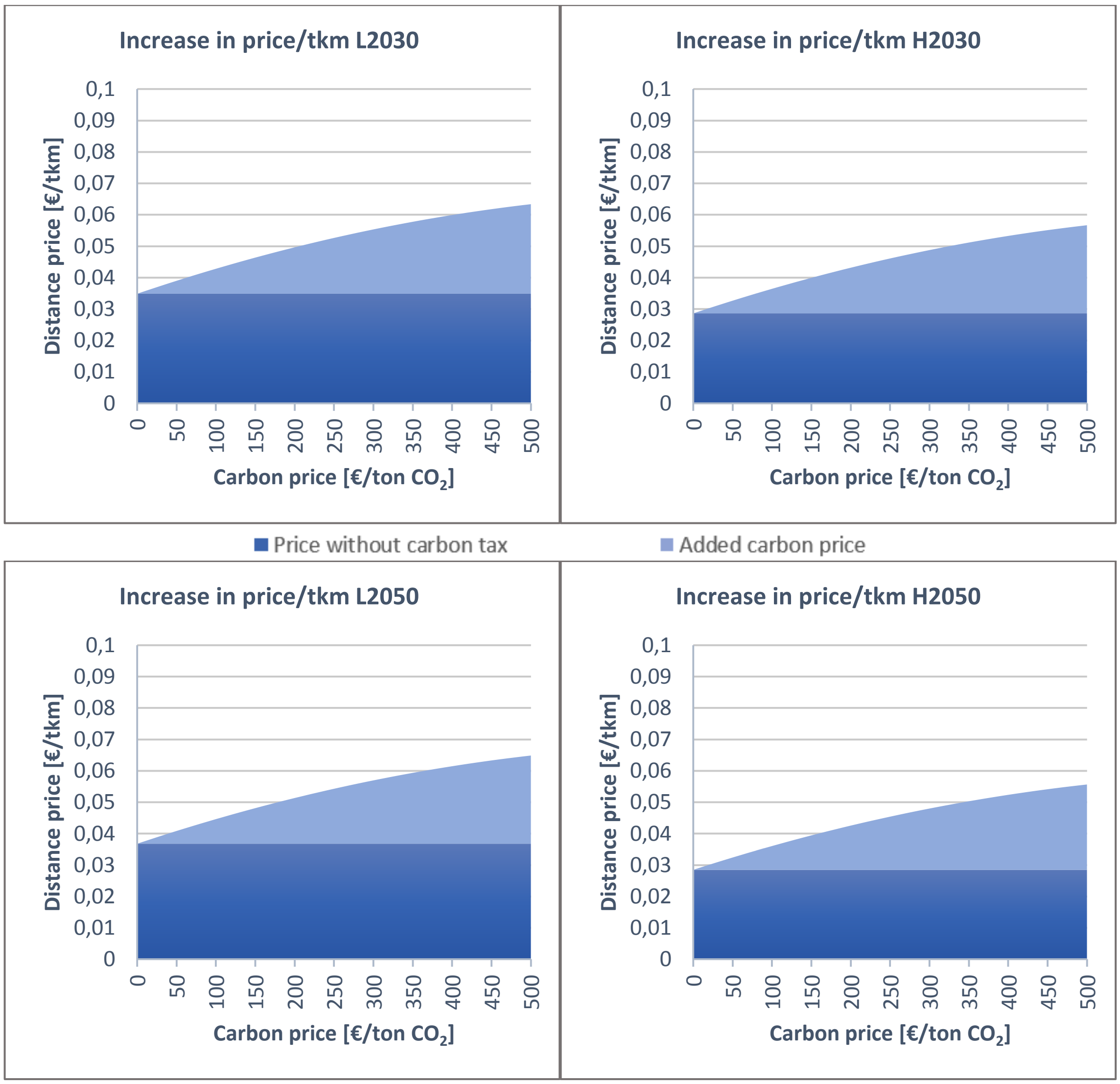

Figure A.6: Increase in price/tkm for the different scenarios for road transportation using diesel

Increase in IWW price/tkm per scenario

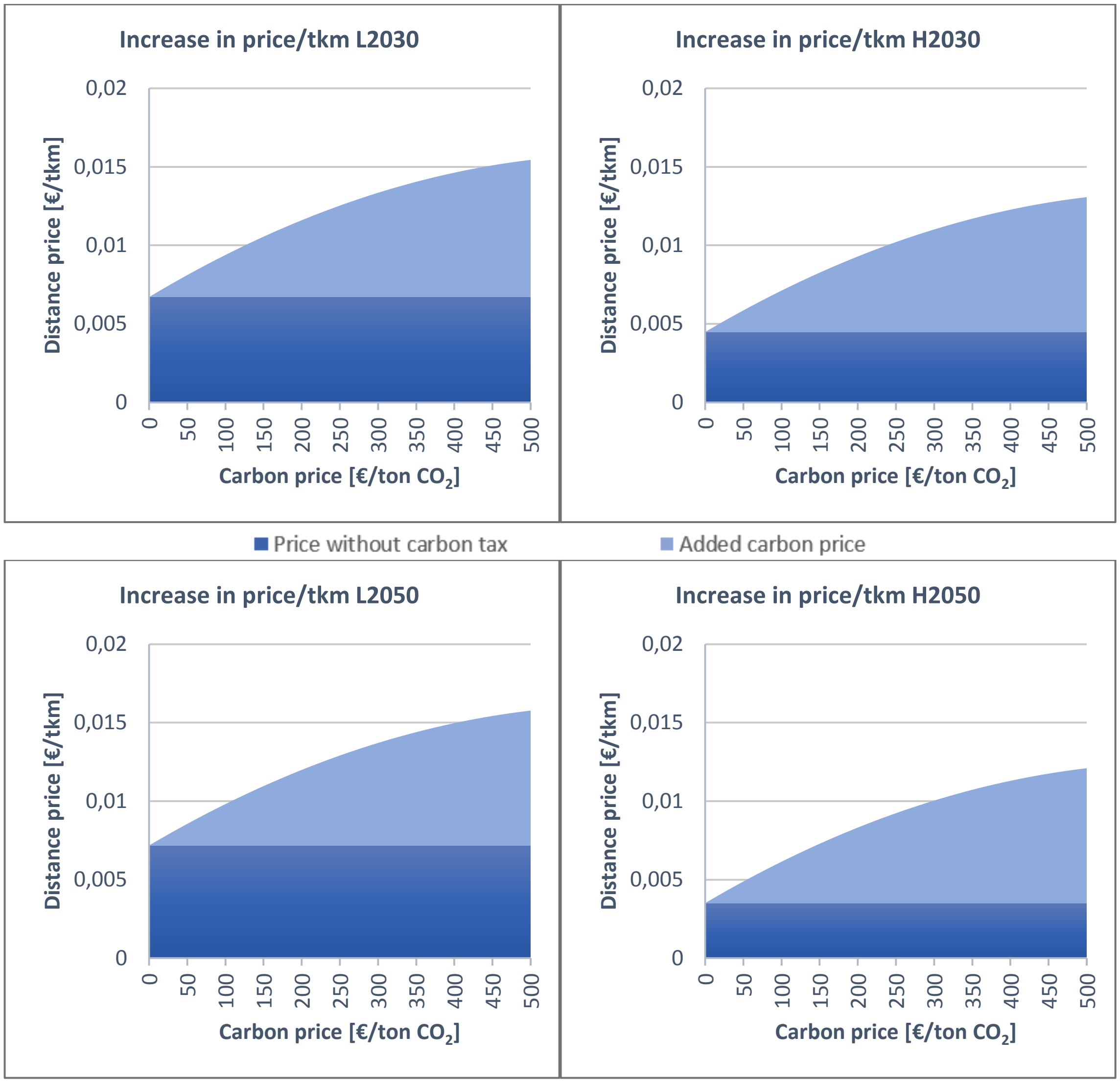

Figure A.7: Increase in price/tkm for the different scenarios for IWW transportation

Increase in rail price/tkm per scenario

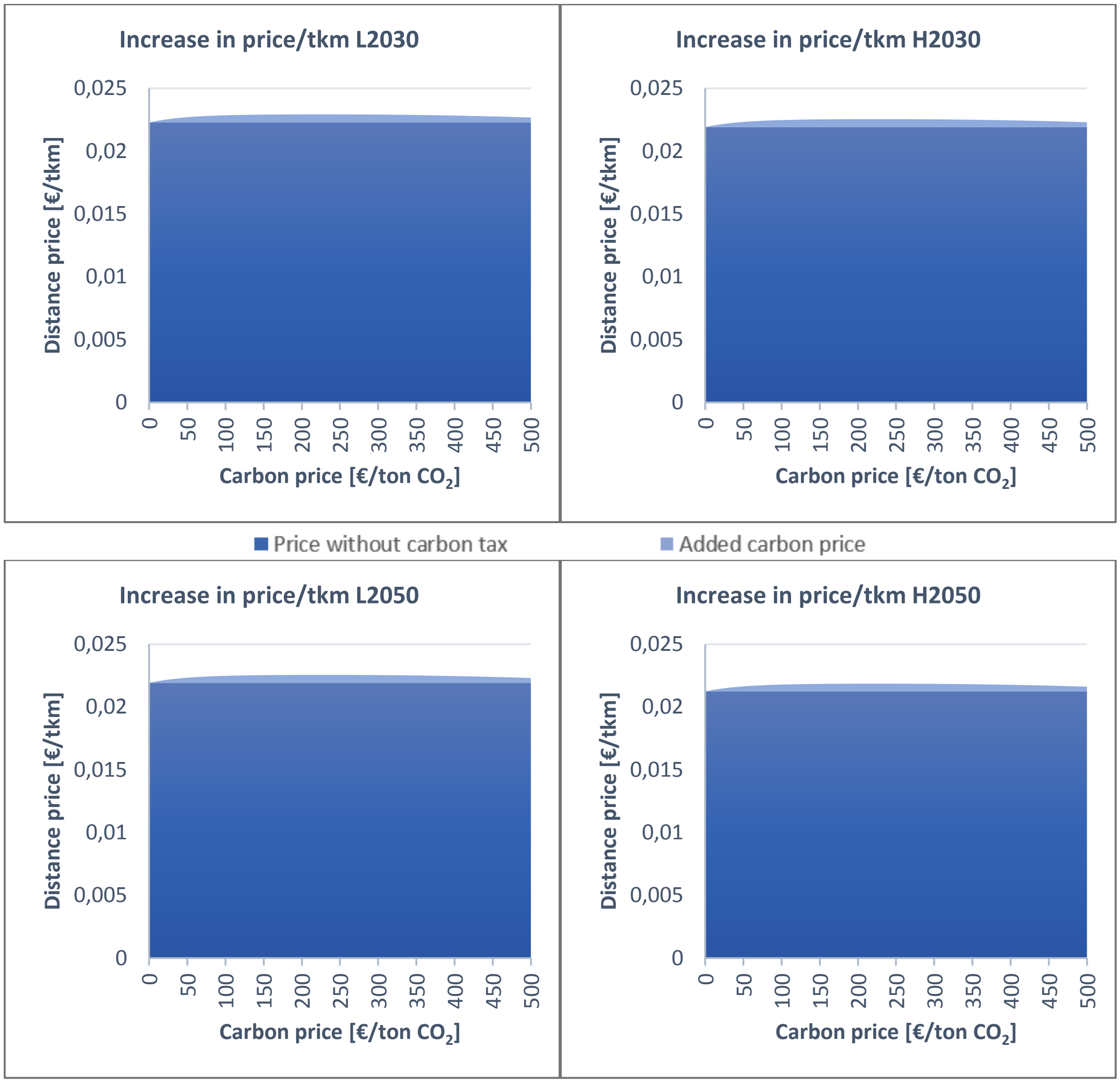

Figure A.8: Increase in price/tkm for the different scenarios for rail transportation

Increase in road using electricity price/tkm per scenario

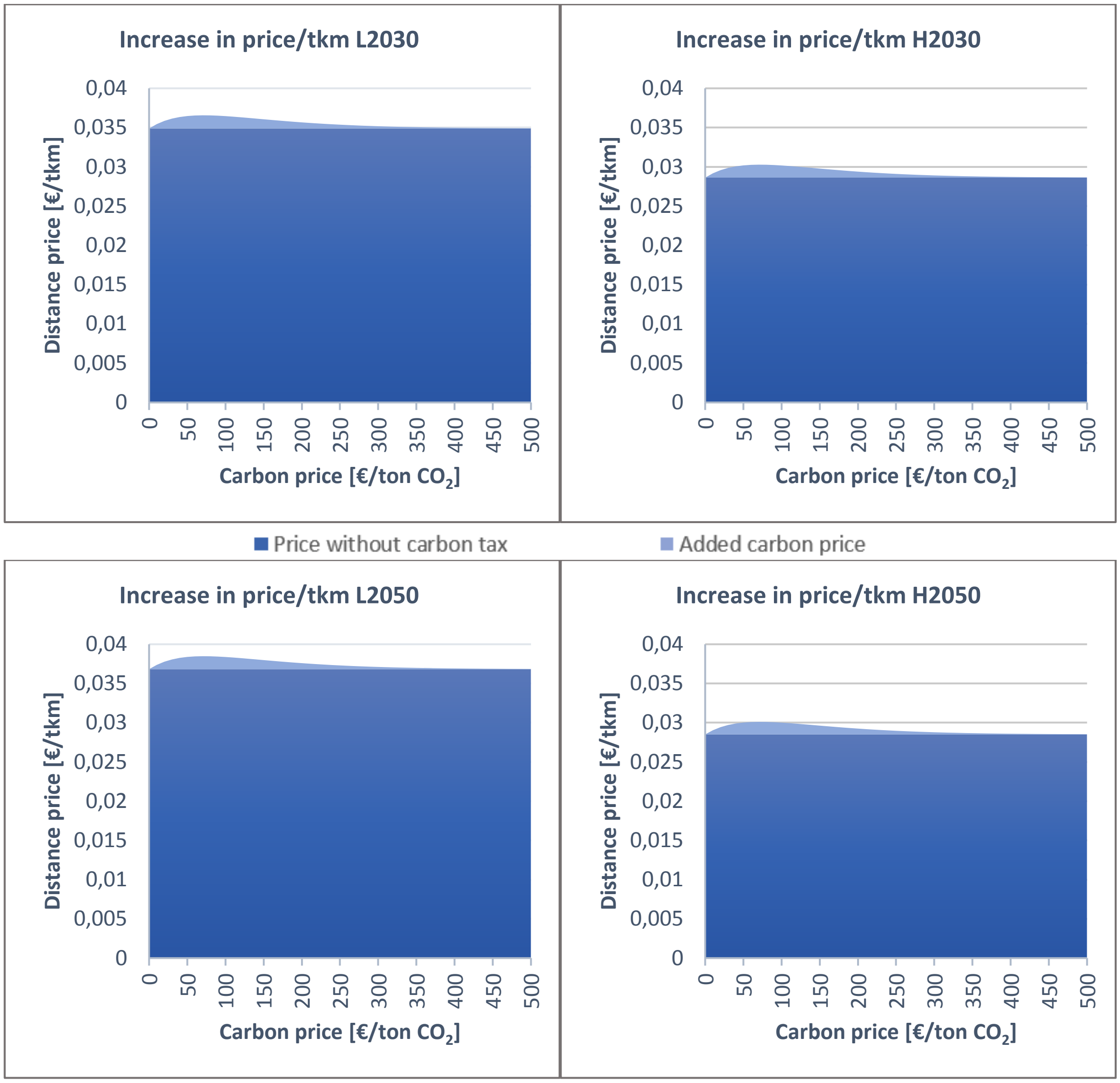

Figure A.9: Increase in price/tkm for the different scenarios for road transportation using electricity

G. Modal split per carbon price level

Figure A.10 shows the modal split per carbon price level per scenario. Only a minor change can be found; the share of road decreases until a carbon price of €330 for each scenario. At this price the BEVs are introduced to the road mode which increases the total share of the mode. The freight mainly shifts to the IWW and back, resulting in an increase in the share of IWW until €330, followed by a decrease again between the carbon price of €330-€500.The share of the rail increases slowly. However, this increase is less than 0.5 percentage points.

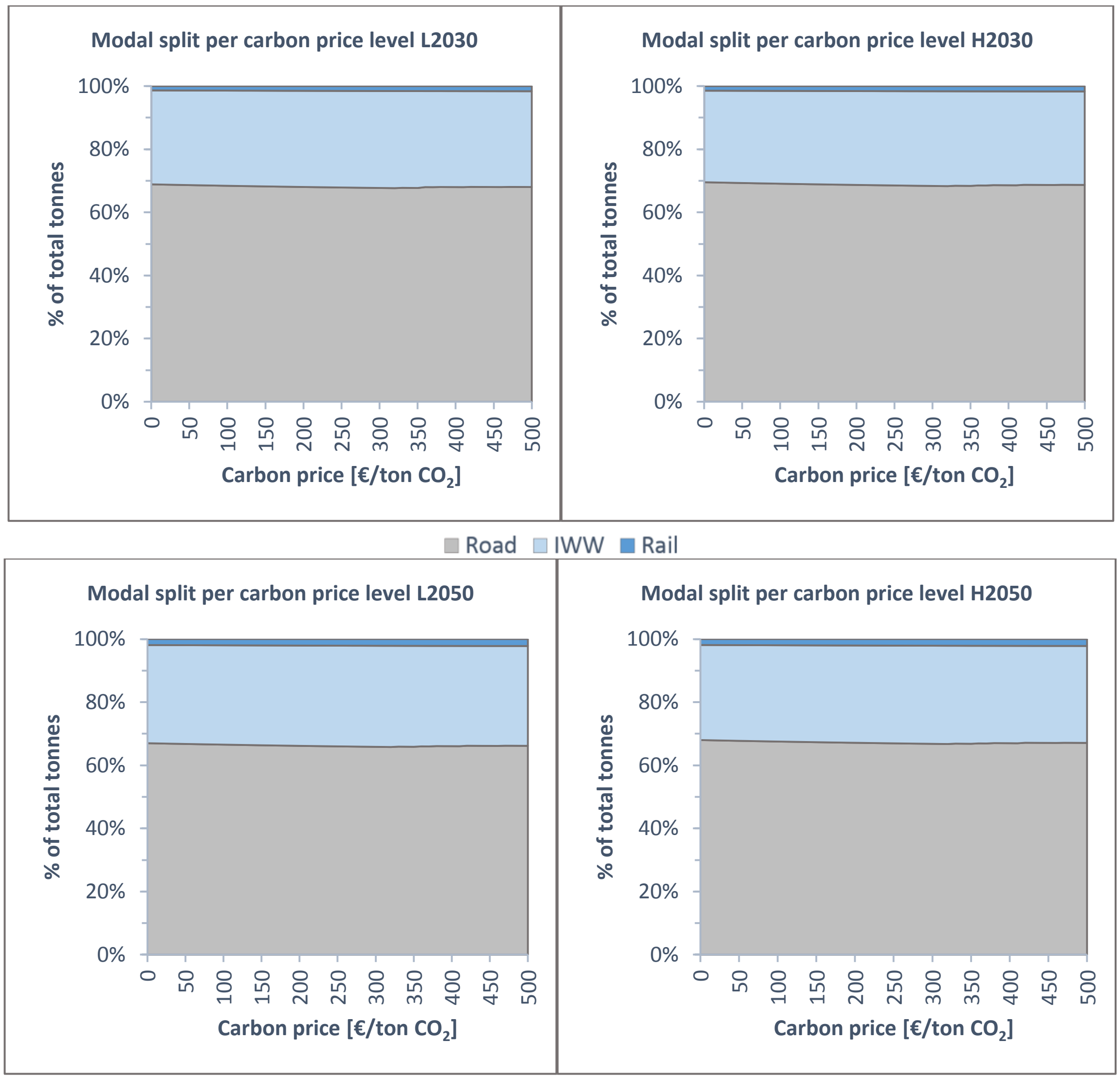

Figure A.10: Modal split (% of tonnes) per carbon price level per scenario

H. Modal shift per distance class

The effect of the carbon price on the modal split differs per distance class. When BEVs are available, more freight will shift towards road transportation, while in the ranges where electric road transportation is not available, rail and IWW transportation will become cheaper which results in a shift towards those modes. The figures below show the modal shift (in percentage of the amount of tonnes that were originally transported by road) to IWW and rail per carbon tax levels €100, €200, €300, €400 and €500 per scenario per distance class.

Modal shift per distance class in the Low 2030 scenario

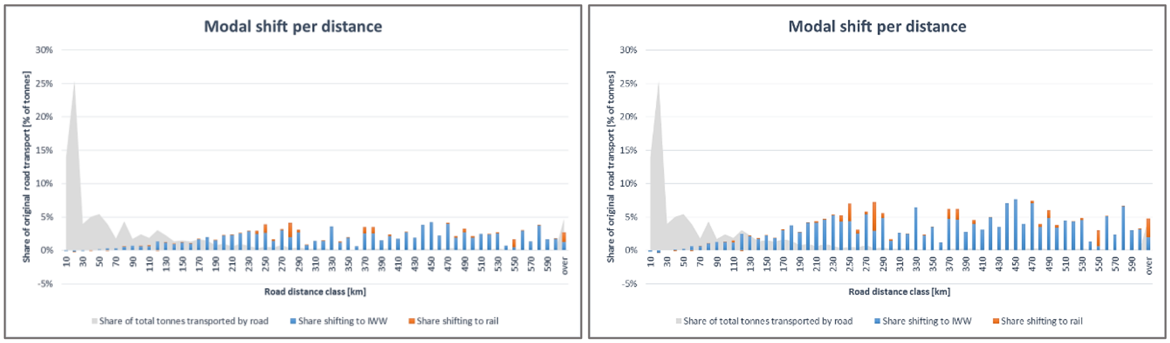

Figure A.11: Modal shift in the low 2030 scenario (€100 left, €200 right)

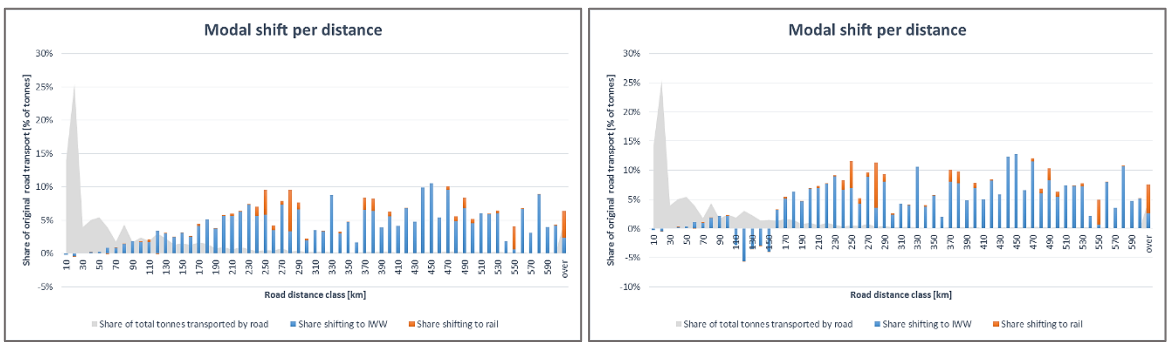

Figure A.12: Modal shift in the low 2030 scenario (€300 left, €400 right)

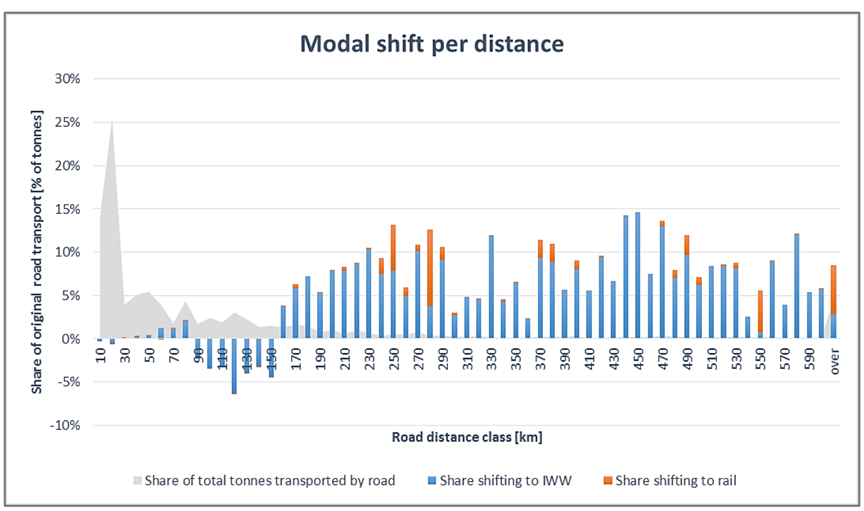

Figure A.13: Modal shift in the low 2030 scenario (€500)

Modal shift in the High 2030 scenario

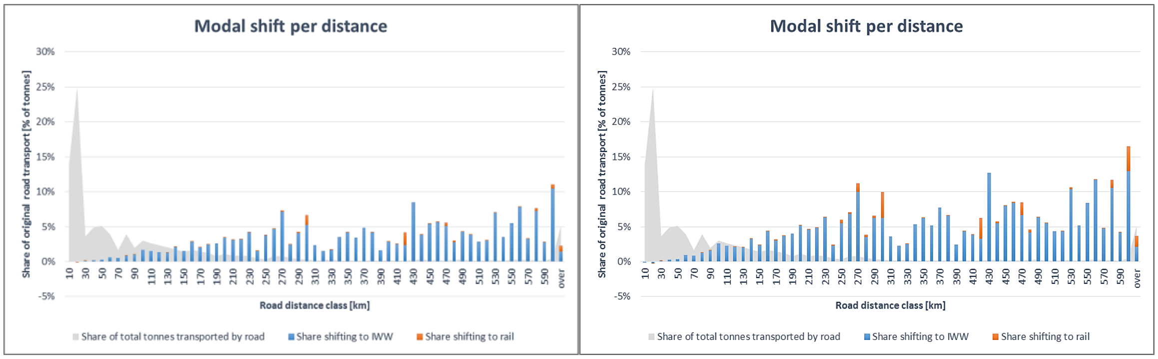

Figure A.14: Modal shift in the high 2030 scenario (€100 left, €200 right)

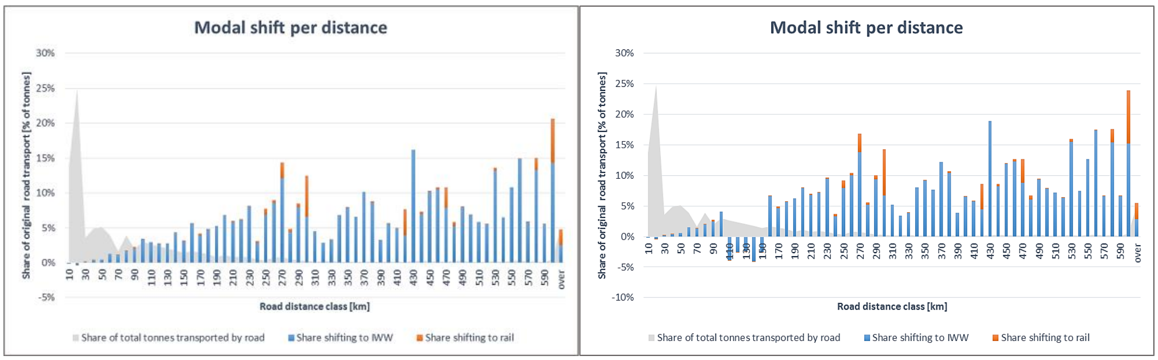

Figure A.15: Modal shift in the high 2030 scenario (€300 left, €400 right)

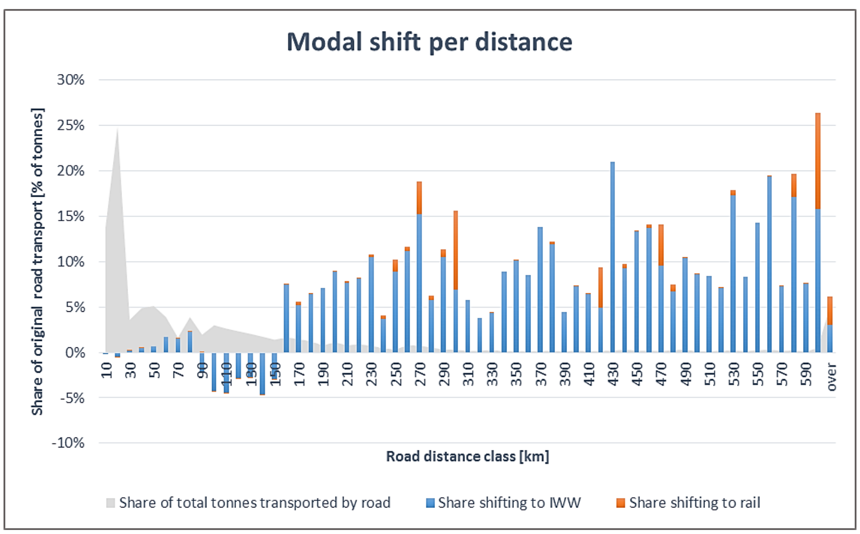

Figure A.16: Modal shift in the high 2030 scenario (€500)

Modal shift in the Low 2050 scenario

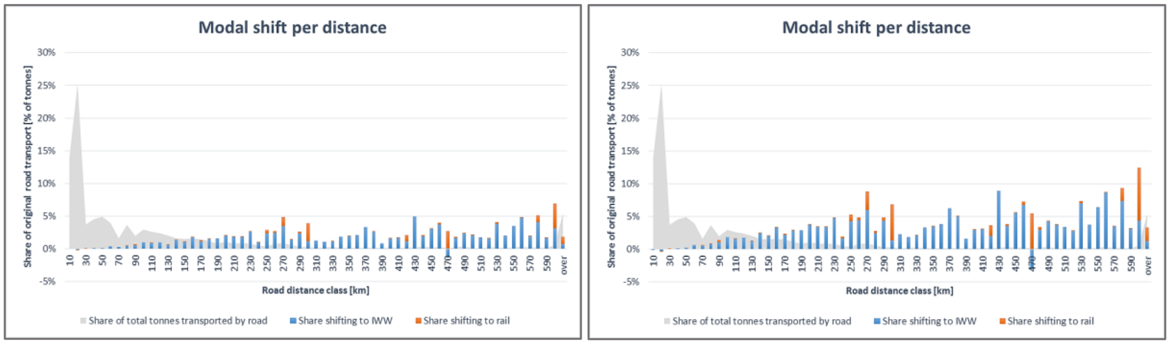

Figure A.17: Modal shift in the low 2050 scenario (€100 left, €200 right)

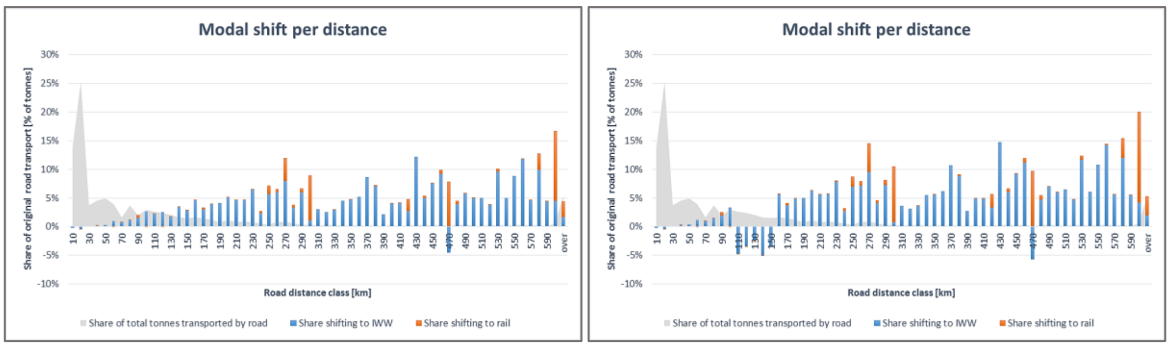

Figure A.18: Modal shift in the low 2050 scenario (€300 left, €400 right)

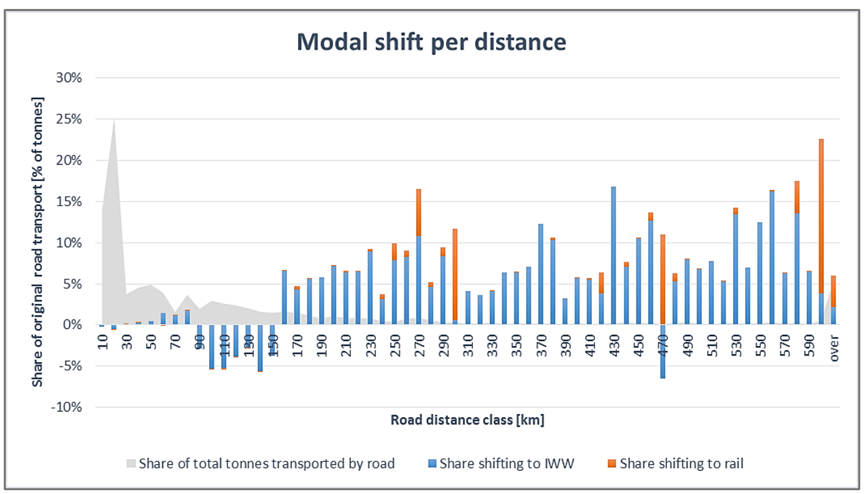

Figure A.19: Modal shift in the low 2050 scenario (€500)

Modal shift in the High 2050 scenario

Figure A.20: Modal shift in the high 2050 scenario (€100 left, €200 right)

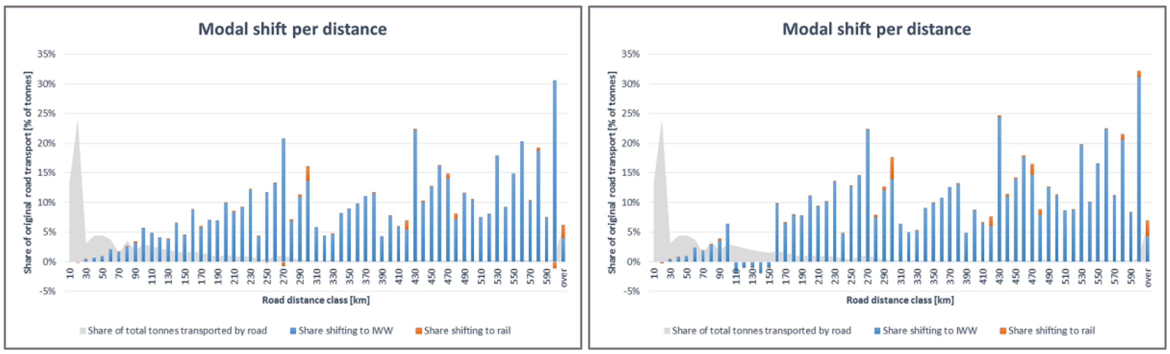

Figure A.21: Modal shift in the high 2050 scenario (€300 left, €400, right)

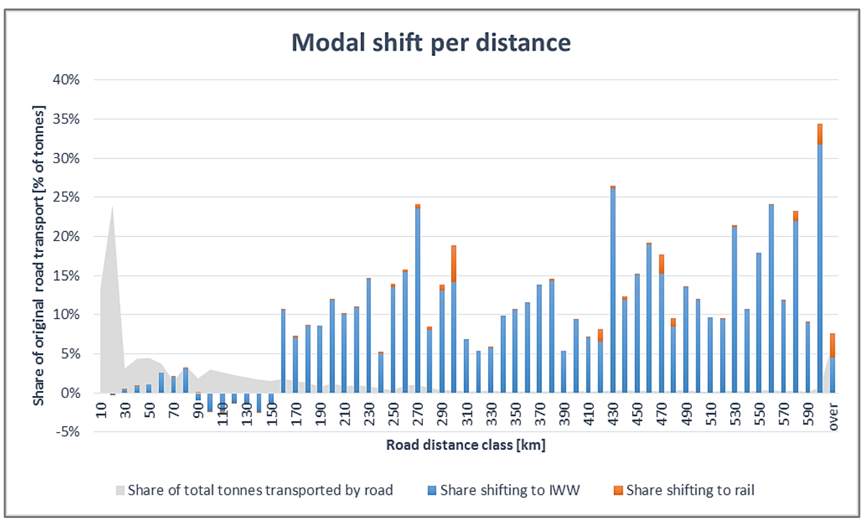

Figure A.22: Modal shift in the high 2050 scenario €500

I. TOTAL SYSTEM COSTS PER SCENARIO

The total system costs are calculated using equation 5, the cost formula from BasGoed. This equation adds the different type of costs: the (un)loading costs, the time costs and the distance costs. The figures below show the course of the different type of costs per carbon tax level per scenario. All the scenarios show the same trend when considering the cost types: the distance costs, the time costs and the (un)loading costs are decreasing gradually until the point where BEVs are introduced. BEVs result in a shift towards the road mode, resulting in higher (un)loading costs. However, as the BEVs cause a decrease in the carbon costs that must be paid, the total system cost increases less when a new range becomes available.

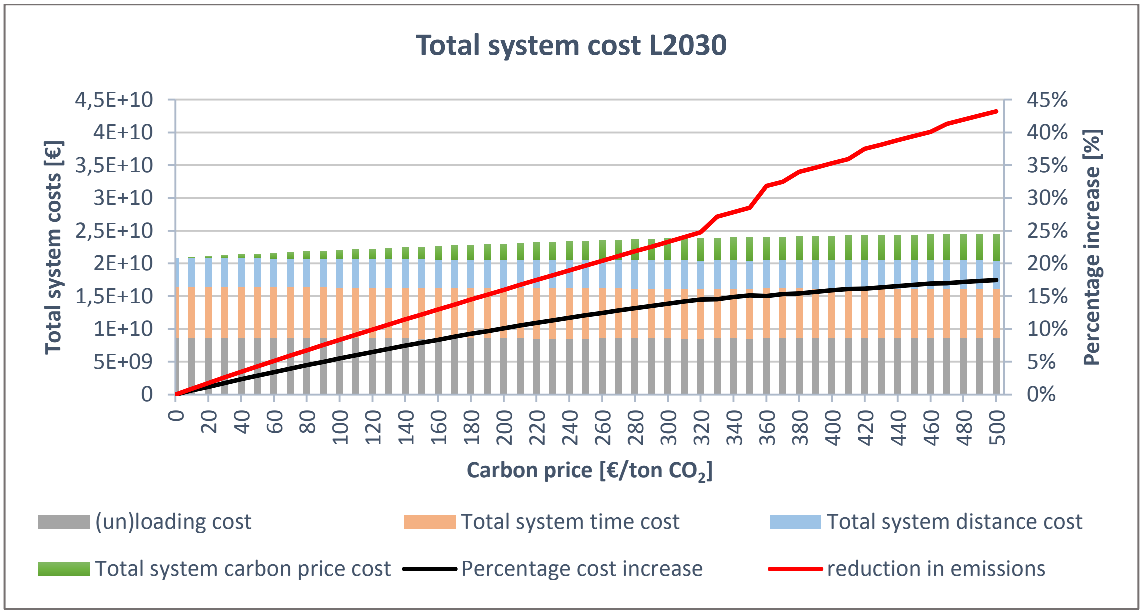

Figure A.23: Total system cost in the low 2030 scenario per carbon price level

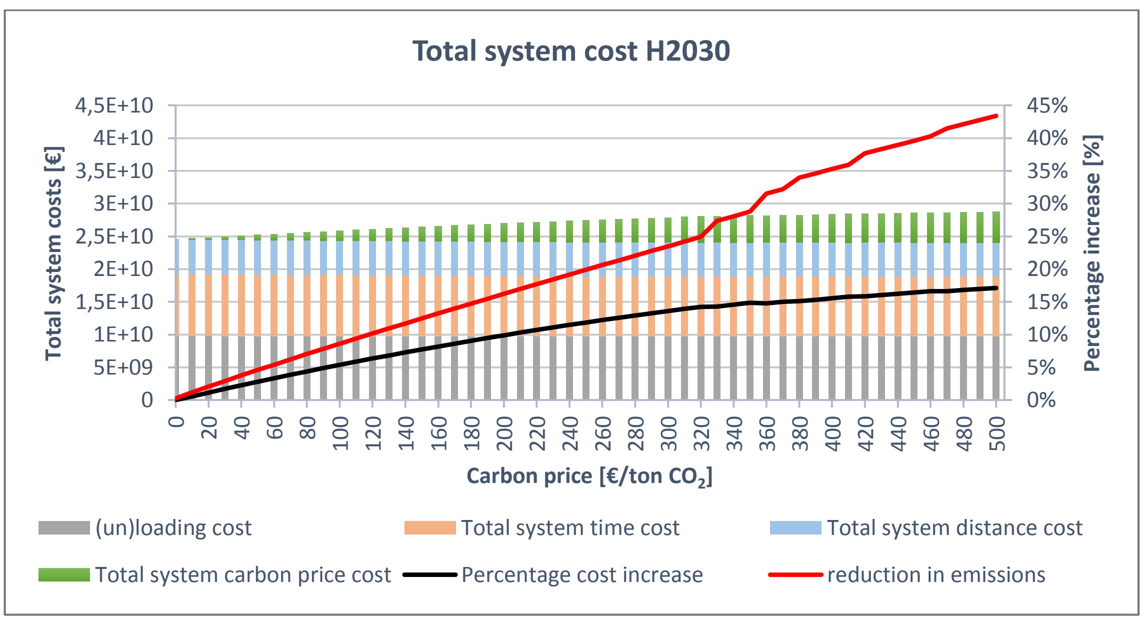

Figure A.24: Total system cost in the high 2030 scenario per carbon price level

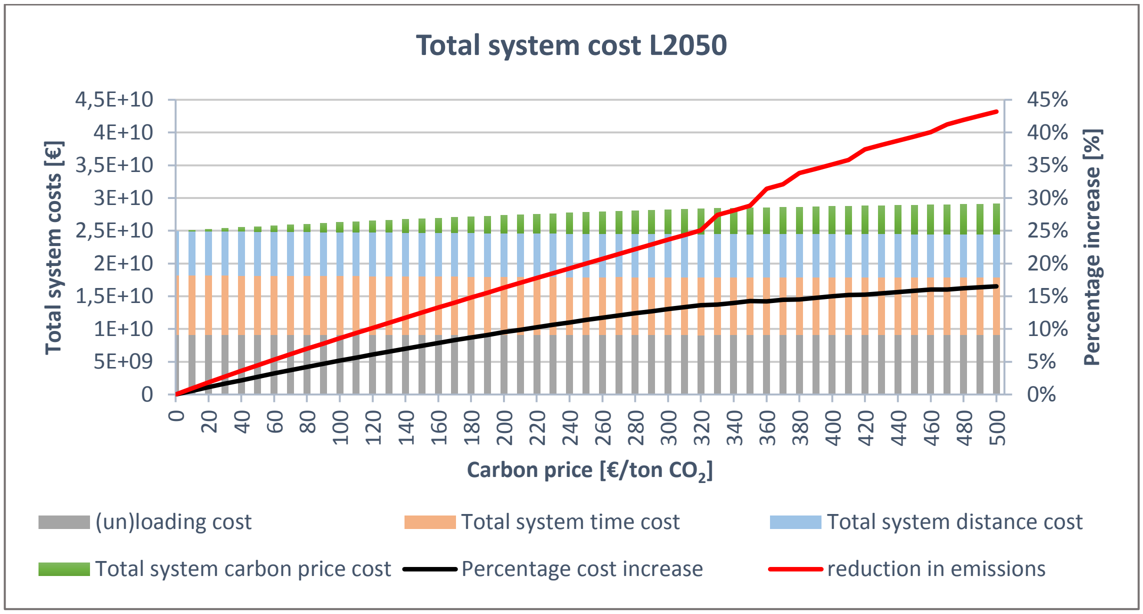

Figure A.25: Total system cost in the low 2050 scenario per carbon price level

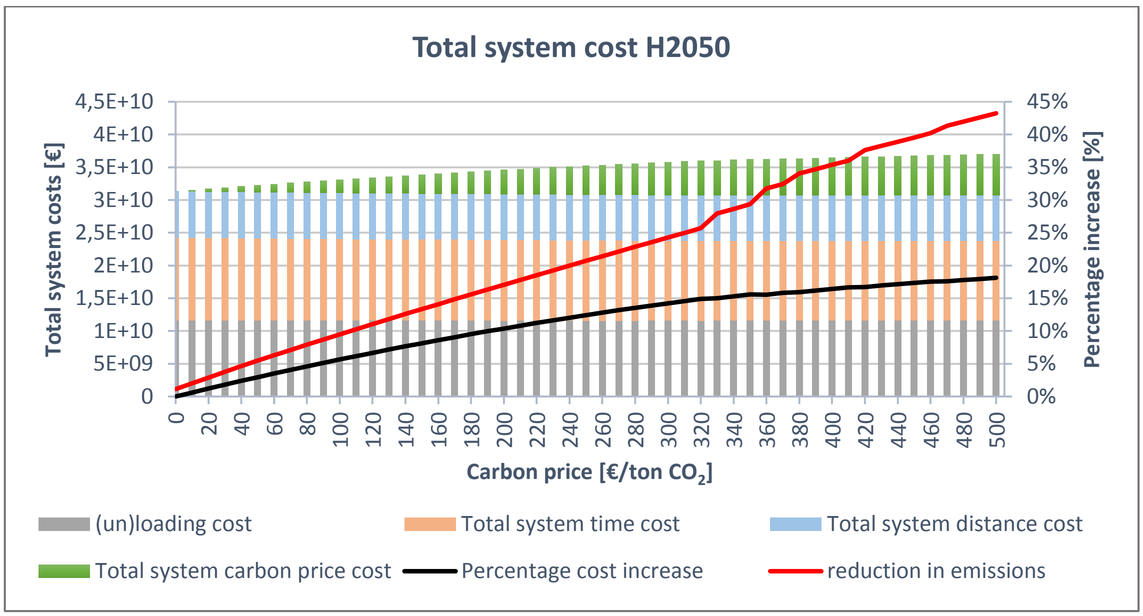

Figure A.26: Total system cost in the high 2050 scenario per carbon price level

J. Sensitivity Analysis

A sensitivity analysis is performed to research the influence of the uncertainties of the study. Three sensitivity analyses are performed in which the influence on the outcome of the reduction in emissions is shown.

Sensitivity of the reduction in emissions due to the influence on the energy generation market

Chapter 3.2 describes the assumption of the decrease of the emissions of the conventional diesel vehicles by an increase in the vehicle efficiency and technology. Next to that, it is assumed that a reduction takes place in the electricity generation market due to an increasing share of renewable energy when the carbon price is introduced. This has resulted in a decrease of the total emissions per mode, explained in chapter 4.4.2. A sensitivity analysis is performed by changing the rate of the reduction in emissions. The rate is increased and decreased by 20% and 50%. This results in the emissions per mode per carbon tax level as shown in Figure A.27.

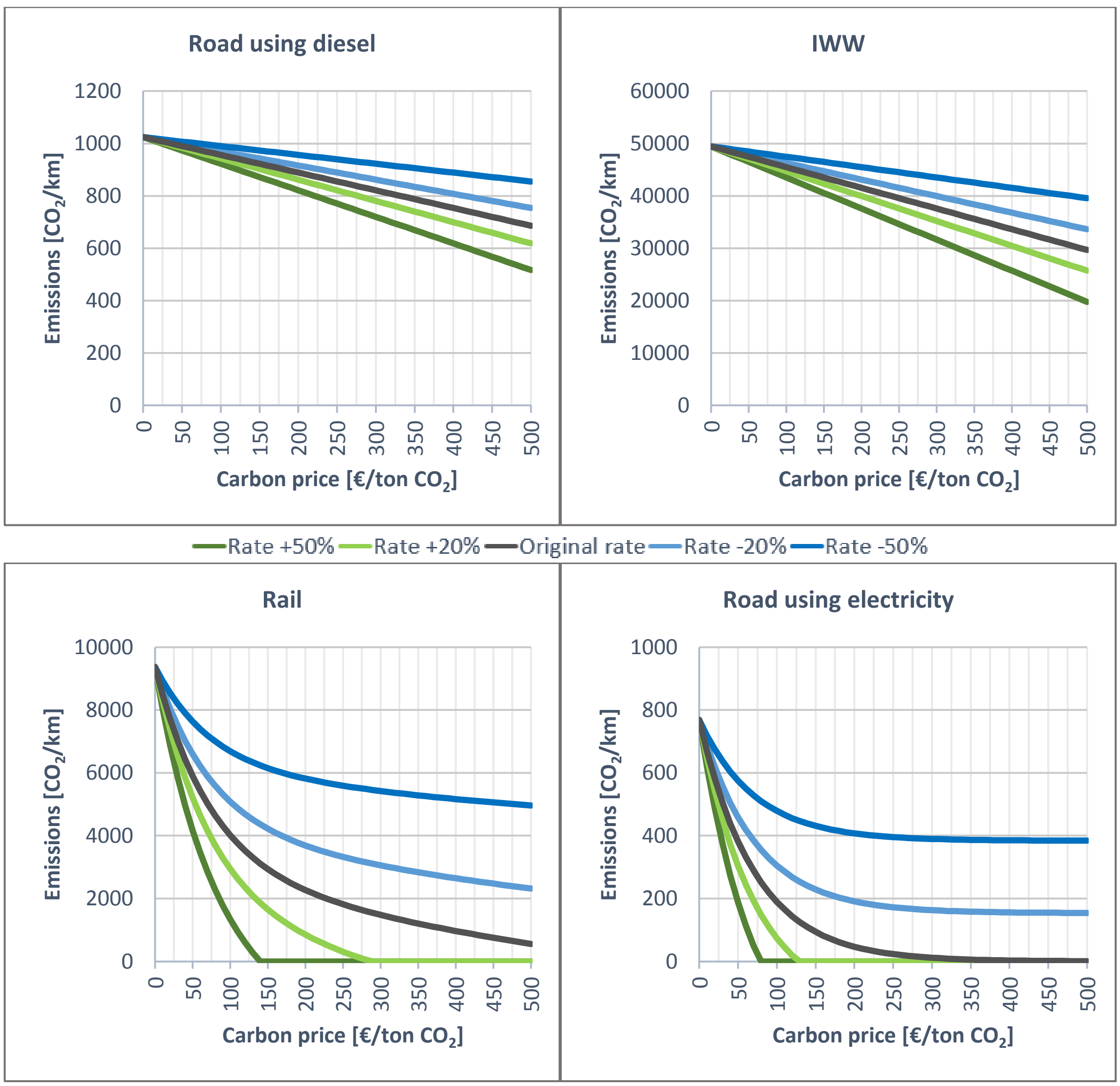

Figure A.27: Emissions per mode per carbon tax level with a changing decrease rate

The differences in emissions result in a varying BEV range for the different inputs. Figure A.28 shows the Ranges for the BEVs per decrease rate. Note that when the rate decreases with 50%, BEVs do not become an economically viable option. The conclusion can be drawn that the decrease of the emissions of the BEVs is important to become economically viable. On the other hand, when the rate is increased with 50%, the BEV range is smaller and becomes available at a higher price. This results from a faster decrease of the diesel emissions which makes the price increase of the diesel vehicles not enough to create the advantage for BEVs.

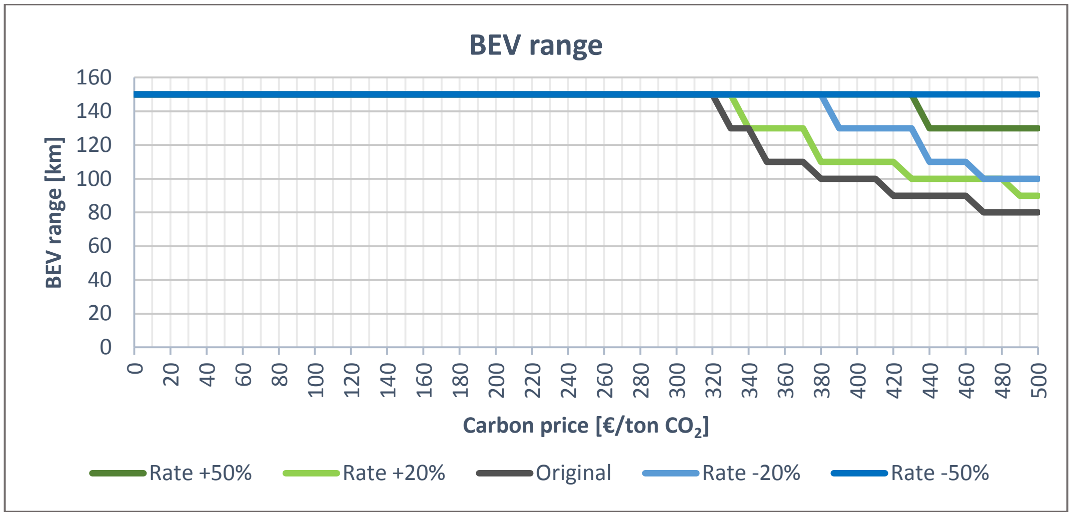

Figure A.28: BEV range for the different decrease rates

The results of the varying rates on the reduction in emissions for the High 2050 scenario is shown in Figure A.29. When the decrease of the emissions slows down, the reduction in emissions decreases much; when the rate is decreased with 50% and 20%, the resulting reductions are 51% and 20% when compared to the original reduction rate respectively. When the rate increases with 20% and 50%, the resulting reductions increase with 13% and 28% when compared to the original decrease rate, respectively.

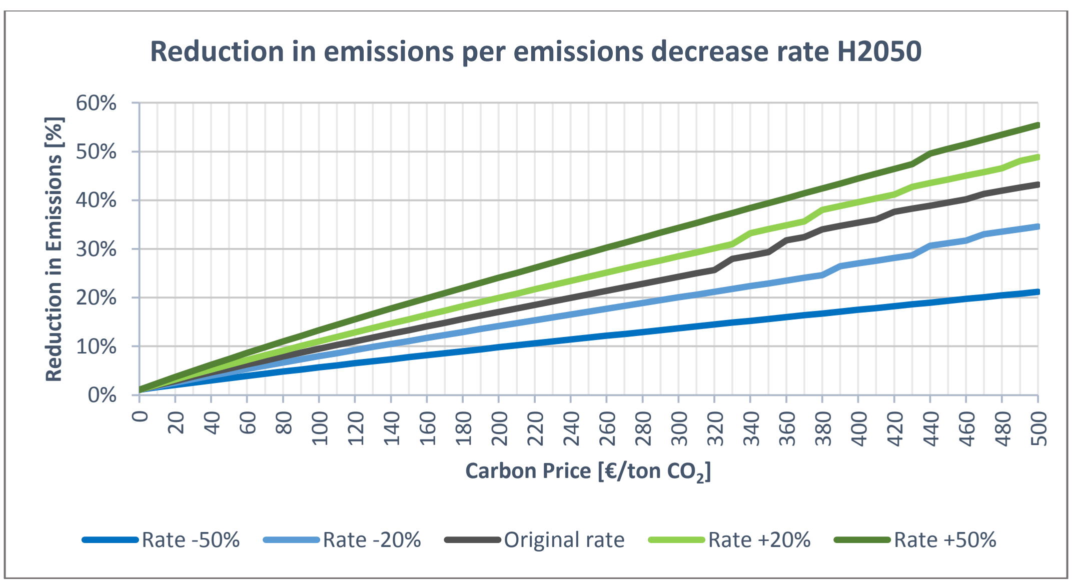

Figure A.29: Sensitivity of the emissions reduction to influence on the energy generation market

Sensitivity of the reduction of emissions due to a change in the maximum range of electric vehicles

The range for the BEVs is dependent on the maximum range of the vehicles. When the maximum range increases, more conventional diesel vehicles will be able to shift to BEVs. The sensitivity of the maximum range is researched by varying the maximum with a decrease and increase of 20 and 50 km. Figure A.30 shows the impact of the maximum BEV range on the reduction in emissions. The BEVs become an economically viable option at a smaller carbon price when the range increases. When the range increases with 20 and 50 km, the reduction in emissions increases with 3.6% and 7.7% at a price of €500 respectively. When the range decreases with 20 and 50 km, the reduction in emissions decrease with 3.1% and 8.6% at a price of €500 respectively.

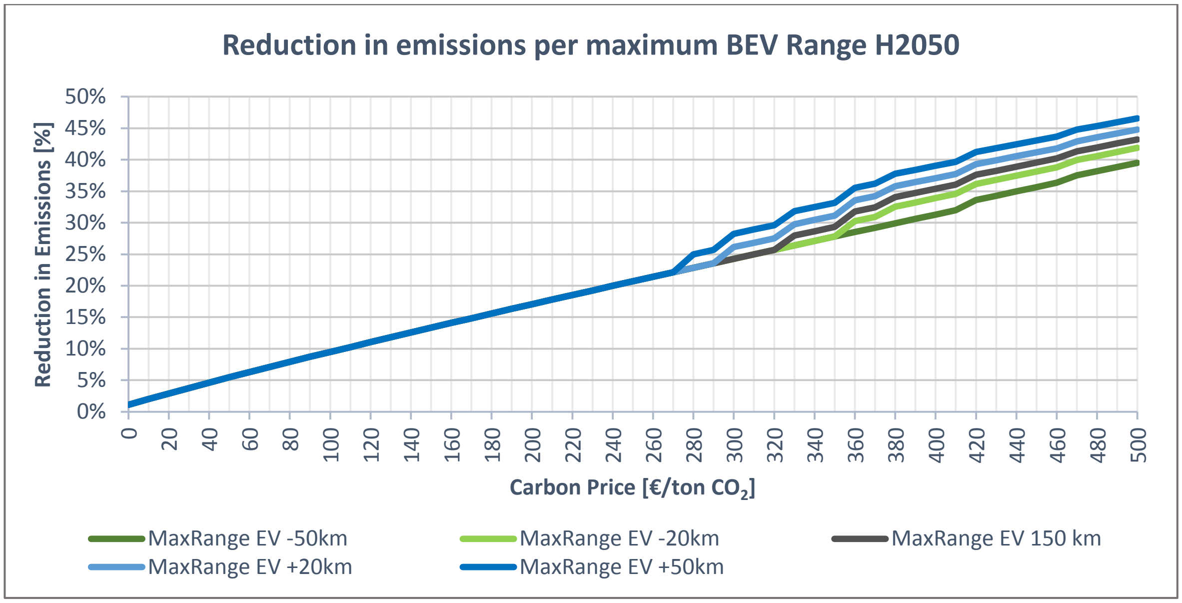

Figure A.30: Sensitivity of the reduction in emissions to the maximum BEV range in the H2050 scenario

Sensitivity of the reduction of emissions due to a difference in the starting emissions

The emissions of the modes were determined in chapter 4.4.2. An average was calculated per mode using the data from CE Delft. A sensitivity analysis is performed on these emissions by increasing and decreasing the emissions with 10% and 30%. The resulting emissions per vehicle are shown in Figure A.31. Note that the decrease of the emissions per mode stay at the same rate, resulting in a smaller difference between the sensitivity scenarios at a higher carbon price.

The changing emissions affect the range where BEVs become cheaper as the emissions of diesel vehicles increase or decrease compared to the BEVs. The resulting BEV ranges are shown in Figure A.32. When the emissions of the modes are 30% higher, BEVs become a cost-attractive option at a lower carbon price. Next to that, the range for BEVs becomes larger at higher prices with a maximum range of 50 - 150 km, allowing a part of the access transportation to IWW and railways service station to be performed by BEVs. When the emissions are decreased with 30% the BEVs do not become cheaper at all within the carbon price range of €0-€500.

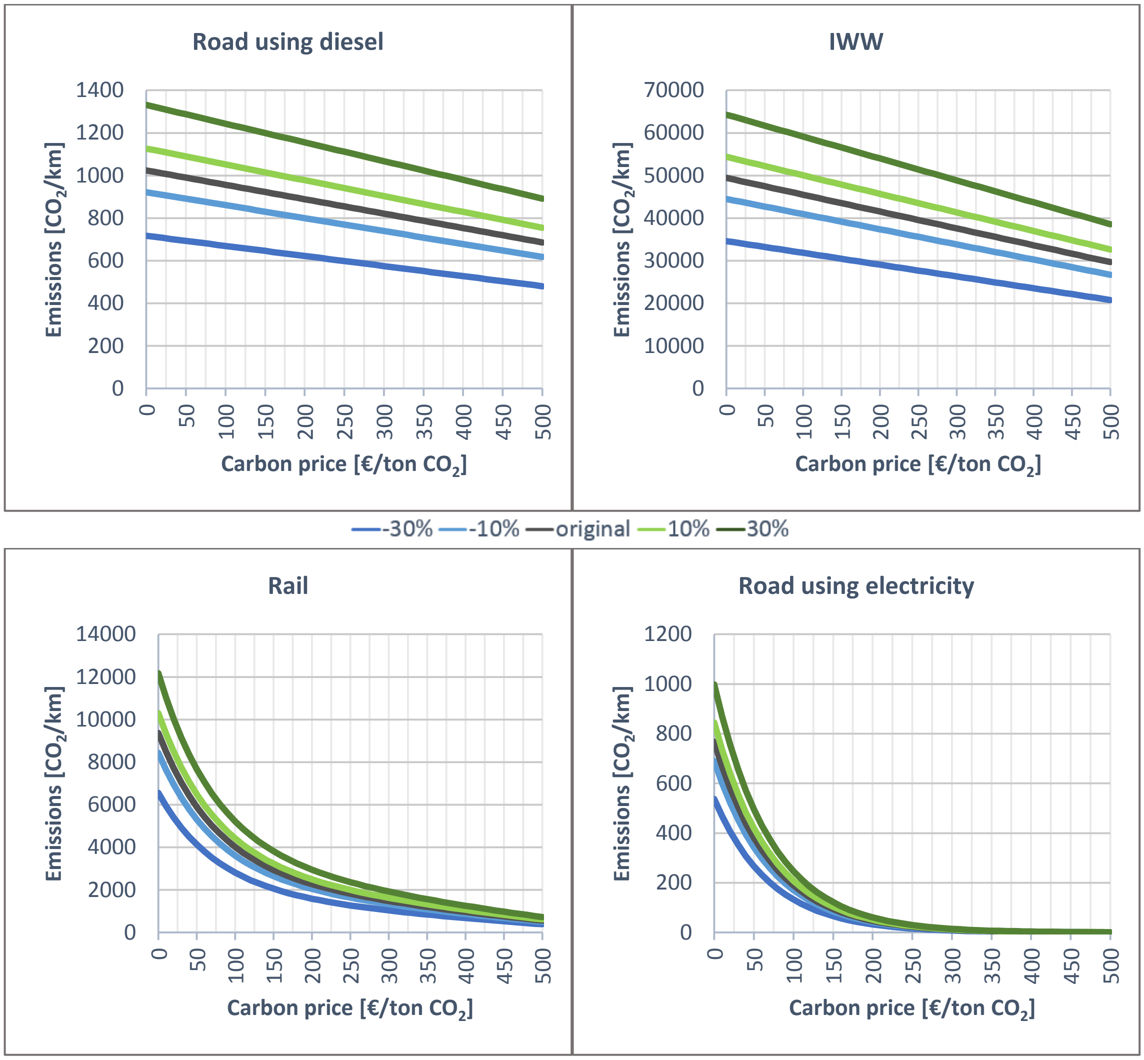

Figure A.31: Emissions per mode per carbon tax level with a different amount of emission

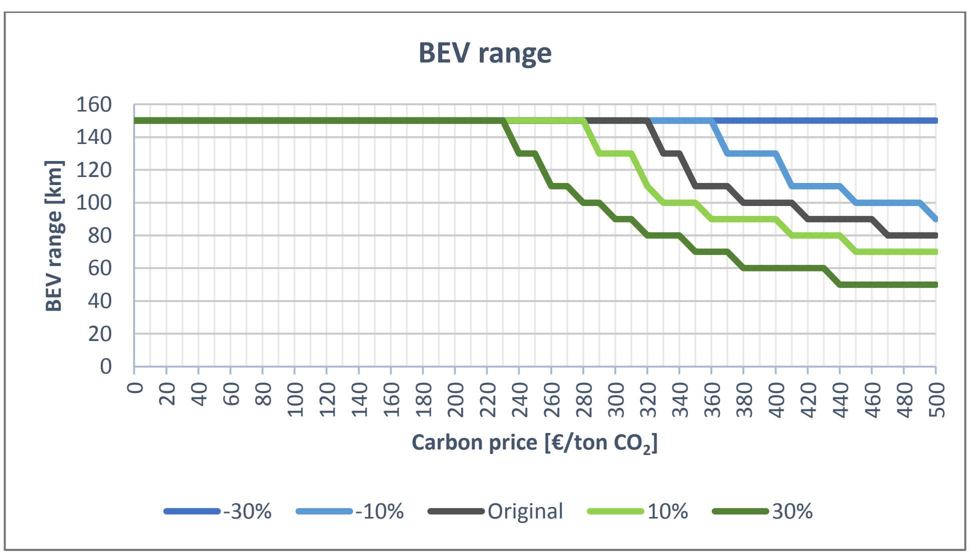

Figure A.32: BEV range for the different amount of emissions

Figure A.33 shows the reduction in emissions for the different values of the emissions per mode. The reduction in emissions does not differ much per amount of emissions until the point that BEVs are introduced. As the BEVs are introduced at different carbon prices, the reduction in emissions start showing an accelerated decrease at these different prices. This results in different reductions in emissions in the price range of €230 - €500.

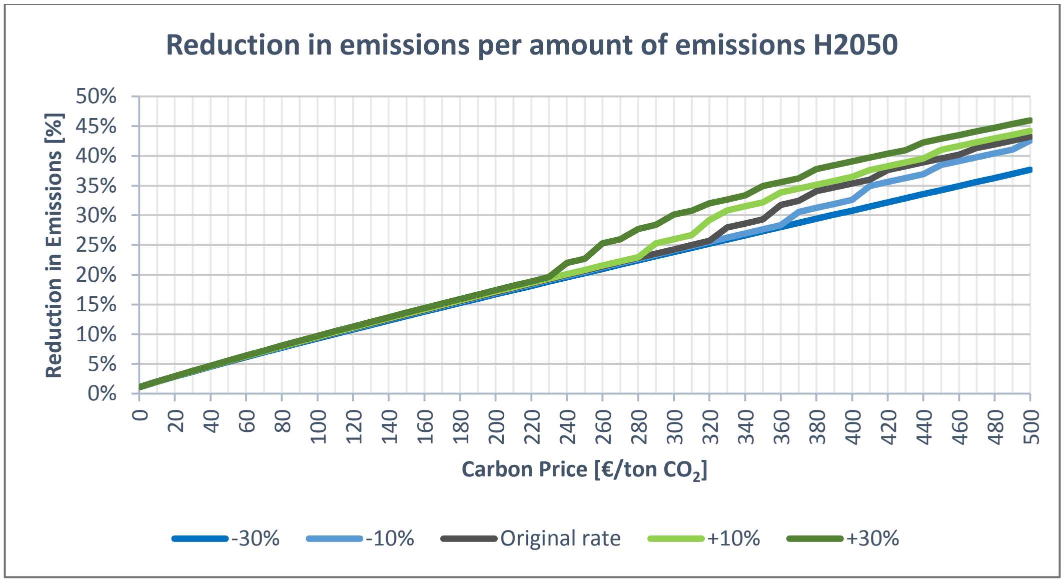

Figure A.33: Sensitivity of the reduction in emissions to the amount of emissions in the H2050 scenario

K. SCIENTIFIC PAPER

Exploring the effects of carbon pricing on the decarbonization of freight transportation in the Netherlands

M.V.I. de Vries

A R T I C L E I N F O

Keywords:
Carbon pricing
Freight transport
CO_2 emissions
Intermodal transport

A B S T R A C T

This paper explores the influence of carbon pricing on three different areas. The carbon pricing causes a decrease in emissions by the different modes by the introduction of new technologies and efficiencies. Next to that, the carbon price enables the use of battery electric freight vehicles (BEVs) and influences the choice of modes. By implementing the carbon price in different models, it is found that BEVs become cheaper in a niche market and the only a slight modal shift occurs. The improvements of the engines increase much, resulting in a decrease of the total CO_2 emissions of the freight transport in the Netherlands.

1. Introduction

Climate change has been an important topic of discussion for the last couple of years. As emissions amplify the global warming, a reduction of emissions is needed. In 2015, the UN climate agreement was signed by the Netherlands, which has the central aim to “strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius” (UNFCCC, 2018). To be able to achieve this, “a reduction of at least 60% of GHGs by 2050 with respect to 1990 is required from the transport sector” (EC, 2011).

Kaack et al. (2018) identified five possible methods to decarbonize freight transport, in which this research focuses on three: increasing the efficiency of freight vehicles, reducing the carbon content of fuel used to transport freight and shifting freight to low carbon-intensity modes.

Increasing the efficiency of freight vehicles refers to the improvement of the technology of conventional diesel vehicles. Vehicle fuel efficiency has a major influence on the vehicle emissions (Taptich et al., 2015). The emissions by vehicles can be reduced by for example improving aerodynamics and engine efficiency of the road mode (ICCT, 2017), line layouts and rolling stock for rail (International union of Railways, 2016) and hydrodynamic measures and the optimisation of the ships speed for IWW (CCNR, 2012). Even though the high potential of the energy savings, some barriers are identified regarding the adoption of the new technologies. The new technologies can be expensive and there is an uncertainty in exploring the new technologies (Kaack et al, 2018).

By reducing the carbon content of fuel, the CO_2 emissions of transport can directly be reduced. Currently freight vehicles depend on predominantly diesel, which is responsible for the increase of the

CO_2 in the atmosphere (Singh et al., 2015). Possible alternative fuels are Biodiesel, Electricity, Ethanol, Hydrogen, Methanol, Natural Gas, LPG, Solar energy and P-series fuel (Johnston et al., 2005). However, even though alternative fuels are generally better for the environment (e.g. less emissions and quieter vehicles) and only little has to be adjusted, vehicles using alternative fuels are expensive and the supply of the alternative fuels is uncertain as it is a relatively new technology (McKinnon et al., 2010).

By shifting freight to low carbon-intensity modes, a shift away from road freight transport is meant, as the average carbon intensity of intermodal transport is 46% lower than truckload (Craig et al., 2013). The European commission has tried to promote this shift away from road, however, this has not resulted in a significant change. Jonkeren et al. (2019) state that this is because "it is often difficult for policy makers to assess how rail and inland waterways can attract cargo"

One way to promote the three methods that can decarbonize transport is to introduce a price for the CO_2 emissions. By including the external effects of each mode, the transportation modes that emit less CO_2 can be promoted (Beuthe et al, 2002). Next to the promotion of other transport modes, carbon pricing can also influence the decision to use alternative fuels as this might become a cheaper option. Furthermore, when transport planners must pay for the emissions, investing in new technologies that enable transportation with less emissions becomes attractive.

This study explores the effects of carbon pricing on the freight transport in the Netherlands when considering the emissions per mode, the sources of energy and a modal shift. By exploring the effects, the possible reduction in CO_2 emissions is determined. The study considers the modes road, inland waterway (IWW) and rail and looks at the alternative fuel electricity.

The paper is structured as follows: section 2 presents the freight transportation sector in the Netherlands. Section 3 explains the methodology on how the analysis is performed. The section introduces the use of two existing models for the simulation of the effects. These models are explained and the way the battery electric vehicles (BEVs) and the increase in the prices of the modes are introduced to the models is elaborated. Section 4 presents the results of the analysis, followed by a discussion and conclusion in section 5.

2. Freight transportation in the Netherlands: flows and emissions

Each mode has its characteristics, which makes the mode suitable for a certain type of goods or certain type of transport. Therefore, the mode characteristics are important decisive factors for the modal split. The importance of the characteristics of modalities differs for transport planners. According to Kopytov & Abramov (2012) the choice of transportation route depends on costs, time, reliability and ecological aspects. Bask & Rajahonka (2017) summarized the selection criteria in several papers and found that costs are the most important according to literature. Next to that, reliability, time and flexibility are important factors. Sustainability is also mentioned several times, but scores lowest when looking at the total score.

When looking at the freight transport in the Netherlands, road freight transportation is the most used mode. Road transport is more expensive than IWW and rail but the network is very dense which enables transportation without transhipments between different modes. Even though road freight transport is fast, road traffic is the mode that experiences the most accidents, decreasing the reliability of the transport (Platz, 2009). The road mode is mostly used for domestic transport and is the most popular for the commodities construction and foodstuffs.

IWW freight transportation refers to the transportation by using barges and is the second most used mode for freight transport in the Netherlands (CBS, 2019_b). IWW is a cheap mode of transportation.

However, as transshipment and drayage by trucks is needed, the prices increase. The mode is dependent on the waterways network and the speeds of the network is very low. The mode is used most for ores and oil.

Rail freight transportation is the least used mode for freight transport in the Netherlands (KiM, 2016). Rail freight transport itself can be cheap as the capacity of trains can be large while little personnel is needed and little amount of fuel is needed. However, transferring the goods is expensive which leads to a higher price. The mode is dependent on the railway network which reduces the flexibility. The rail mode could be fast, however due to inefficiencies the average commercial speed is not that fast (Janic, 2008). The mode mostly transports mining and ores.

When looking at the CO_2 emissions of the different modes, a clear difference can be found. The road mode has 2.5 and 5 times as much CO_2 emissions as IWW and rail respectively (KiM, 2016). This means that the mode that emits the most emissions has the largest share while the mode that emits the least emissions has the smallest share of the modal split, resulting in an unsustainable distribution.

3. Methodology

This study researches how the carbon price might affect the reduction of the CO_2 emissions. To simulate this, the influence of the carbon price on three areas is researched. First, the influence of the carbon price on the energy generation market is explained in chapter 3.1. Subsequently, the influence on the choice of fuel by using a vehicle choice model is explained in chapter 3.2. Thereafter, in chapter 3.3, the use of a freight transportation model is explained to be able to research the influence of the carbon price on the choice of the transportation mode. In chapter 3.4, the combination of the models is explained.

3.1 Influence on the energy generation market

3.1.1 Influence of the carbon price on the improvement of conventional diesel vehicles

The emissions of the current diesel engines of the transportation modes can become more sustainable due to technological improvements. ICCT (2017) states that “by improving engine efficiency, aerodynamics, and aftertreatment technology, there is the potential for substantial, highly cost-effective improvements in heavy-duty vehicle efficiency and emissions”. In this study it is assumed that when carbon pricing is introduced, a reduction of CO_2 emissions is reached due to improvements in the technology of trucks, barges and trains.

For the road mode, TNO (2018) found that a decrease of CO_2 emissions from conventional diesel vehicles can be reduced by 28% to 33%. For IWW, a green deal was made that has the goal of decreasing the CO_2 emissions by 40% (Rijksoverheid, 2019). For Rail, the International Union of Railways (2016) states that a decrease of emissions of between 20% and 30% is possible by an increase of the efficiency. To reach this, the designs of the trains should be improved, the use of new technologies should be adapted and the designs of the tracks can be improved. In this study, the assumption is made (due to the lack of a relation found in literature) that the maximum reductions of the modes are achieved at a carbon price of €500 and the decrease is linear. Even though this study assumes the decrease, the way the decrease is realised in terms of technology is not included.

3.1.2 Influence of the carbon price on the generation of electricity

CE Delft (2017$_b$) states that the costs of unsustainable production of electricity will increase when the carbon price increases. This leads to the "fuelswitch-effect" which reduces the CO_2 emissions of electricity production. Levin et al. (2019) researched the influence of carbon tax on the generation of electricity and found a decrease in the generation of coal and an increase in the generation by wind when the carbon price increases. To be able to find the related decrease in CO_2 emissions, the CO_2 emissions per kWh are used per generation type. When this is combined with the changes in the shares of the generation types, the CO_2 emissions are found per carbon tax level. To be able to use the decreasing emissions in the study, the relation is extrapolated to a situation of a carbon price of €500. This results in the following formula for the decrease in emissions that is caused by the fuelswitch-effect:

$$e_v^x = e_v^0 * e^{-0{,}014x} \qquad \textit{Eq. 1}$$

With:

e_v^x : The emissions of a vehicle kilometre at carbon price x [CO_2/km]

e_v^0 : The emissions of a vehicle kilometre at a carbon price of 0 [CO_2/km]

x : The carbon price [€/ton CO_2]

3.2 Influence on the choice of fuel

When the carbon price is introduced, the price of the use of unsustainable fuels will increase more than the price of more sustainable fuels. Therefore, alternative fuels vehicles that emit less will become a more attractive option, looking from a cost perspective. Liimatainen et al. (2019) found that several studies conclude that "electric trucks are competitive if annual mileage is high enough and battery lifetime matches the vehicle lifetime". To be able to determine at which carbon price and at which annual mileage the BEVs are becoming a more attractive option than diesel vehicles, a vehicle choice model is used. In this study, the all-or-nothing (AON) algorithm is used for the vehicle choice model. The vehicle with the lowest total costs is chosen. To be able to use the AON algorithm, it must be assumed that the same attributes are considered and that the transport planners weigh them in the same way. This results in that every transport planner makes the same decision (Ortúzar & Willumsen, 2011).

The Panteia TCO model is used for the modelling of the vehicle choice: conventional diesel vehicles or BEVs. For both vehicle types, the total costs are determined using the factors in table 1. The carbon tax is added to the model in the factor 'variable costs per km'. To be able to perform the analysis, the TCO model needs the type of vehicle, the mileage per year and the carbon tax as inputs. As the methodology needs only one vehicle type to be used as input for the model, the most used vehicle type in the Netherlands is chosen: the truck-trailer (CBS, 2018$_b$). The mileage per year and the carbon tax are varied as inputs to be able to come to the result of the TCO analysis: at which carbon tax level and for which mileage per year are the costs for BEV the same or cheaper than the costs for diesel vehicles.

Factor	Represents
Fixed cost per year	Vehicle road tax Toll Interest (vehicle purchase loan) Insurance Misc. Vehicle costs
Variable costs per km	Depreciation costs (vehicle) Depreciation costs (battery) **Carbon tax** Tires Fuel Electricity Repair/Maintenance
Special transportation costs	-
Private charging system, fixed cost per year	Purchase & installation Operational costs
Driver costs	Hourly Wage Allowances Other costs
General costs (overhead)	Salary costs Building Misc.

Table 1: Factors in the TCO model

3.3 Influence on the choice of mode

When a carbon price is introduced, the transport operation will become more expensive, with the less sustainable modes getting more expensive than the more sustainable modes. Therefore, the carbon price will influence the choice of the transportation mode. To be able to see the influence that the carbon price has on the choice of modes, a freight transportation model is used. In this study, a discrete choice model is used as a freight transportation model. Discrete choice models use the concept of "utility" to represent the attractiveness of the alternatives. The characteristics of the alternatives result in, together with the importance of the characteristics, the utility of the alternative. Subsequently, this utility is contrasted to the utilities of the other alternatives to predict whether an alternative is chosen, resulting in a probability value between 0 and 1 (Ortúzar & Willumsen, 2011).

This study uses the BasGoed model as a freight transportation model. The BasGoed model is used in the Netherlands for the estimation of the production and consumption of the zones and the corresponding flows per mode (de Jong et al., 2011). The BasGoed model consists out of 4 modules; the freight generation module, the distribution module, the modal split module and the assignment module. As this study uses the BasGoed model for the choice of modes, only the modal split module is used. The structure of the modal split module is shown in figure 1.

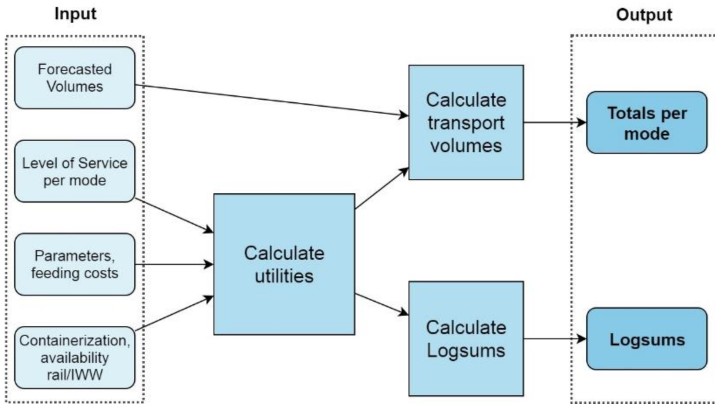

Figure 1: Modal split module structure of BasGoed (Authors figure)

To be able to determine the modal split, the module calculates the utility using the costs, the time, the containerization, whether a border is crossed and constants that refer to the preference of taking a certain mode per origin, destination and mode (Rijkswaterstaat, 2018). To be able to come to the costs of a certain route, the costs formula is used (equation 2). However, the use of the formula differs per commodity type. For mining, oil and ores the pre- and end drayage is not taken into account as it is assumed that the origins and destinations are located at an IWW or rail service station. For construction only the arrival feedings costs are taken into account as it is assumed that the origin of the freight is located at a service station of rail or IWW and the destination is located elsewhere.

$$c_{ijvg} = d_{iv}^{acc} \cdot T_g^{road} + d_{jv}^{egr} \cdot T_g^{road} + d_{ijv}^{itr} \cdot T_{vg} + t_{iv}^{acc} \cdot R_g^{road} + t_{jv}^{egr} \cdot R_g^{road} + t_{ijv}^{itr} \cdot R_{vg} + 2 \cdot Unload_{vg} \qquad eq.\ 2$$

With:

d^{acc}	:	Distance to reach access for a train or IWW terminal
T_g^{road}	:	Average distance costs for transporting commodity g over the road
d_{jv}^{egr}	:	Distance from the terminal to the destination
d_{ijv}^{itr}	:	Distance from i to j with mode v
T_{vg}	:	Average distance costs for commodity type g with mode v
t^{acc}	:	Time to reach access for a train of IWW terminal
R_g^{road}	:	Costs per time unit for commodity g over the road
t_{jv}^{egr}	:	Time to transport the goods from the terminal to the destination
t_{ijv}^{itr}	:	Time from i to j with mode v
R_{vg}	:	Costs per time unit for commodity type g with mode v
$Unload_{vg}$	:	Unloading costs for commodity g with mode v

To add the carbon price to the costs of the routes, the carbon price is added to the distance related costs (T) by determining the emissions cost rate using the formula:

Emissions cost rate: $e_v^x \cdot x$ *eq. 3*

With:

e_v^x : Emissions per vehicle kilometre at carbon price x [ton CO_2/km]

x : The carbon price [€/ton CO_2]

The well-to-wheel emissions per vehicle kilometre are determined using the report from CE Delft (2017_a). The influences on the energy generation market are taken into account, resulting in a different emissions level per mode at the different carbon prices.

3.4 Bringing the models together

The outcome of the TCO model gives the range where BEVs are chosen over diesel vehicles per price level. This is introduced to BasGoed by making the road mode switch 100% to BEVs within the resulting distance range. It is assumed that the costs and other factors of the road mode are the same for BEVs. However, due to the difference in emissions between BEVs and diesel, a price differentiation arises.

To be able to explore the effects of the carbon pricing, the carbon price is varied from €0-€500 in steps of €10. The study uses four scenario from the BasGoed model: Low 2030 (L2030), High 2030 (H2030), Low 2050 (L2050) and High 2050 (H2050). The difference between the high and low scenarios is created by expected differences in economic factors, international policy, logistics development and national policy.

4. Results

4.1 The choice of fuel

When the mileage per year increases, the chance that BEVs become cheaper increases as the investments can be shared over more kilometres. Therefore, the larger distances become cheaper first, followed by the smaller distances. However, the maximum range of BEVs was determined to be 150 km. The range is shown in figure 2 where the blue area shows the range where BEVs are cheaper than diesel vehicles.

The range for the use of electric vehicles is the same for every scenario. The figure shows that from a carbon price of €330 the BEVs start to gain ground. When the price increases, also smaller distances are served by electric vehicles with 80 to 150 km as the largest possible distance range at a price of €500.

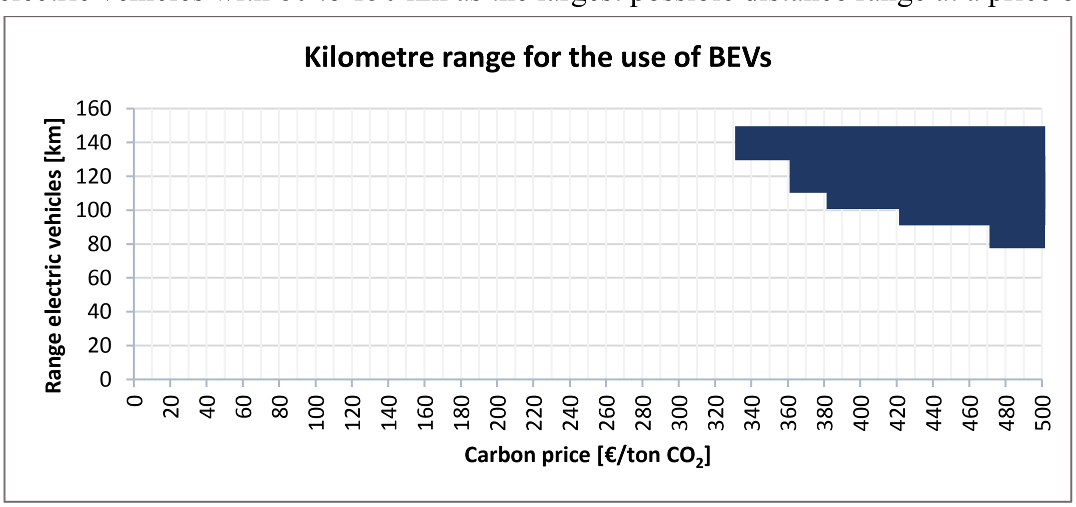

Figure 2: Range for the BEVs

4.2 The choice of modes

Figure 3 shows the modal split of the tkm of the different modes for the high 2030 scenario. The figure shows that the amount of tkm of road transport using diesel is slowly decreasing. When BEVs are introduced the decrease of the road mode slows down and the BEVs start taking over a part of the tkm transported by road.

For the rail and IWW mode, an increase of their shares takes place. The share of IWW increases the most with 1.46 - 1.8 percentage points. The share of rail increases with 0.91 - 1.11 percentage points, which is different per scenario. Furthermore, the figure shows that BEVs are not used for road transportation that is used to access service station for the IWW and rail mode as the BEV range does not reach these distances. However, due to the shift to IWW and rail, more access transportation is needed, resulting in a slight increase of the share of access transportation by the road mode using diesel.

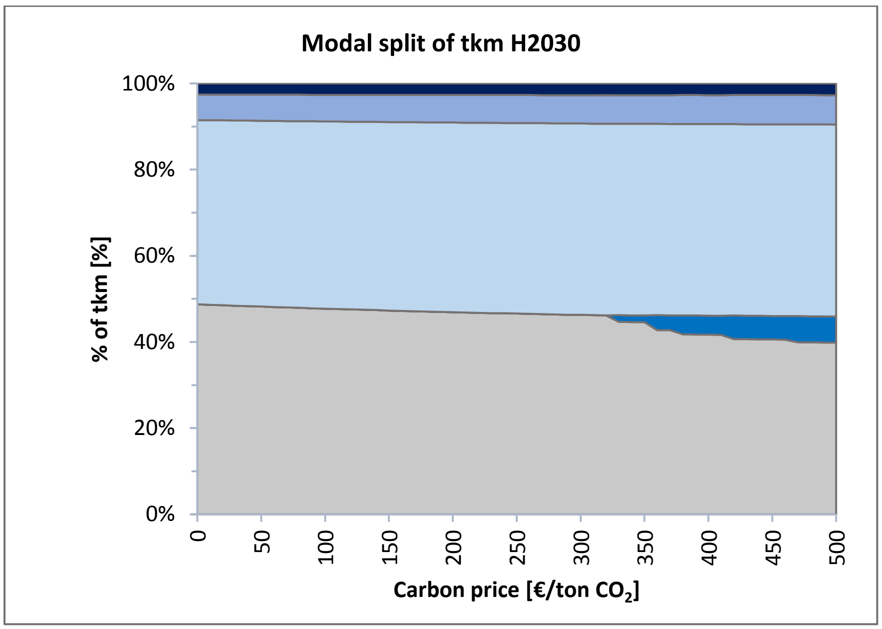

Figure 3: The modal split of the tkm in the H2030 scenario

4.3 Reduction in emissions

Figure 4 shows the reduction in emissions compared to the Basgoed findings without carbon tax per scenario. The scenarios show the same course of the line. The emissions decrease gradually with the introduction of the BEV ranges resulting in an accelerated decrease. For the Low 2030 scenario, the reduction can lead to a maximum of 43.20% at a price of €500 while at the high 2030 scenario the maximum reduction can be 43.10%. For the low 2050 scenario, a carbon price of €500 can lead to a maximum reduction of 43.18% while the high 2050 scenario can lead to a reduction of 43.22%. Note that at a carbon price of 0, the high scenarios already lead to a reduction in emissions due to the ETS price that was reduced from the IWW distance price.

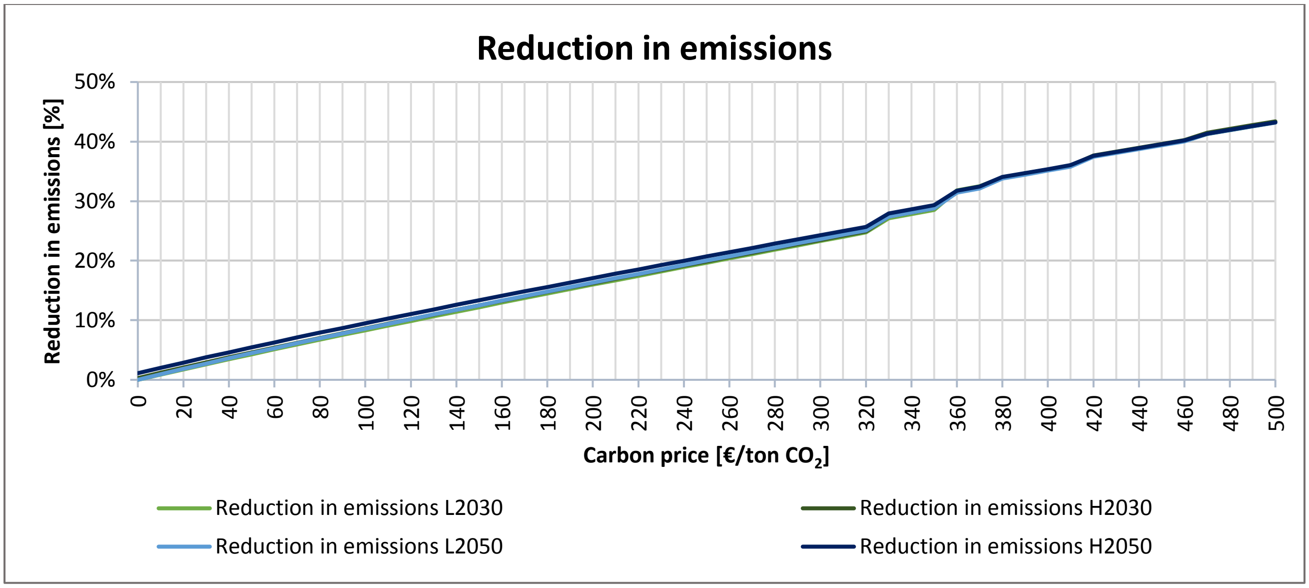

Figure 4: Reduction in emissions

4.4 Total system cost

Figure 5 shows the total system cost of the different scenarios. The total system cost increases gradually, however at a smaller rate than the reduction in emissions. When BEVs are introduced to the system, no increase in the total system cost is shown while the course of the emissions shows an accelerated decrease. Therefore, the introduction of BEVs can be considered as a cost-efficient solution to decrease the emissions. When looking at the total system cost without carbon prices, a decrease is shown (with a maximum value between 1.9% and 2.0%). This is caused by a shift towards cheaper modes (e.g. rail and IWW) which makes the transportation system more cost-efficient. However, this cannot compensate for the increase in the distance costs by the taxes. Therefore, the total increase in the system price is solely caused by the carbon tax that must be paid. Next to the costs, the figure also shows the carbon tax revenues per carbon price. The higher the carbon tax, the higher (logically) the revenue.

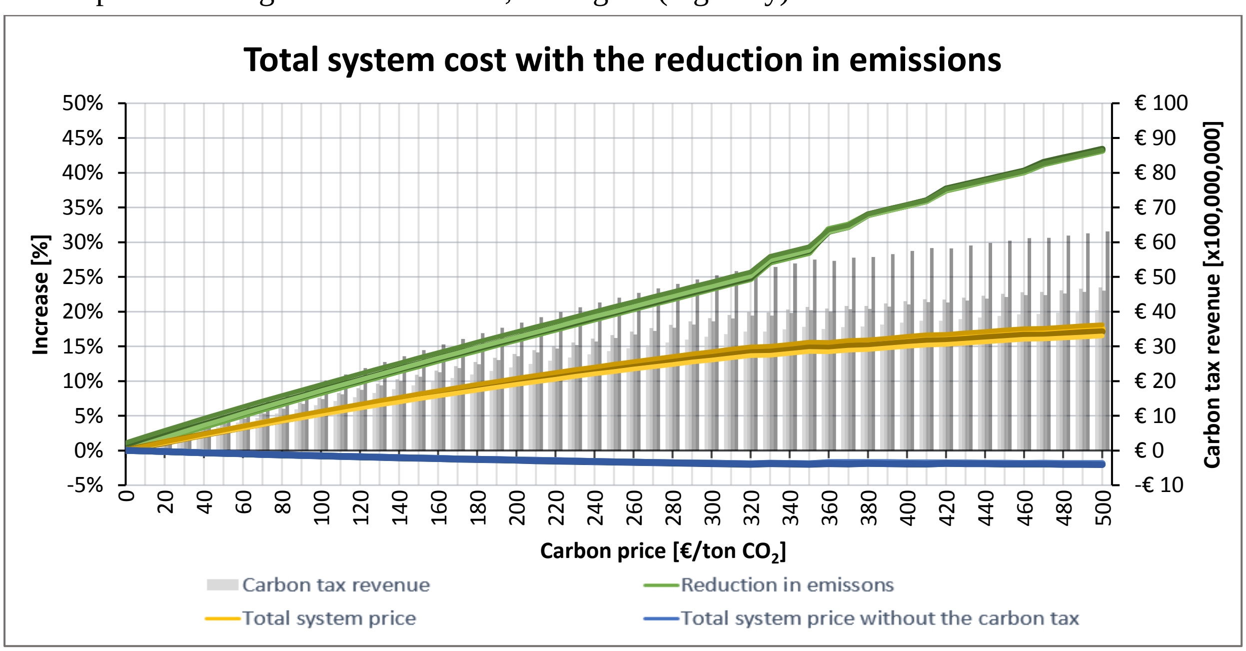

Figure 5: Total system cost

4.5 Sensitivity analysis

Table 2 shows a summary of the results of the sensitivity analysis. The reduction in emissions is very sensitive to the emissions decrease rate, caused by the effect on the energy generation market (e.g. the increase in the vehicle efficiency and the fuelswitch-effect). The reduction in emissions are less sensitive to the maximum BEV range and the emissions of the modes. Therefore, the effects of carbon pricing on the energy generation market seems to be the most important.

	Change	Reduction in emissions	Relative change of reduction in emissions
Original		43.22%	
Emission decrease rate	-50%	21.19%	-50.97%
	-20%	34.58%	-20.00%
	+20%	48.84%	13.00%
	+50%	55.41%	28.21%
Maximum BEV range	-50km	39.51%	-8.59%
	-20km	41.88%	-3.10%
	+20km	44.78%	3.60%
	+50km	46.56%	7.73%
Mode emissions	-30%	37.66%	-12.87%
	-10%	42.58%	-1.49%
	+10%	44.18%	2.22%
	+30%	45.98%	6.38%

Table 2: Sensitivity analysis

5. Discussion and Conclusion

5.1 Discussion

In lack of available literature, the influence of the carbon price on the increasing technology and efficiency of conventional diesel vehicles is assumed. This leads to a big uncertainty in the study, as the sensitivity analysis has shown that the reduction in emissions is very sensitive to this factor. However, it is logical to assume the decrease of the emissions as the possible measures are known (Harvey, 2013) but at the moment too expensive. Next to the decrease in the emissions of the conventional diesel vehicles, the fuel-switch effect is determined by extrapolating the study of Levin et al. (2019). By the extrapolation another uncertainty is introduced. However, as the renewable energy is at the moment available but expensive, this effect can be logically explained.

By the use of the TCO model, the assumption is made that the decision to use BEVs is solely based on cost minimization. However, Seitz et al. (2015) found that for some transport organizations environmental reasons are more important than the cost-efficiency in the adoption of CO_2 saving technologies. This might delay or accelerate the switch to BEVs. Furthermore, for simplifications reasons, the vehicle type truck trailer was chosen to research. However, the costs per vehicle type differ much. For this study, on an aggregate level, these simplifications were needed in order to come to the results.

The results of the TCO analysis have shown that the BEVs become a cheaper alternative than diesel at a carbon price of €330 and higher. First the higher mileages become economically viable, followed by the smaller distances. This is in line with other studies that state that an EV will become relatively more competitive compared to a conventional diesel vehicle with an increasing mileage (Taefi et al., 2017) and with an increasing mileage the carbon pricing becomes more effective as well (Arroyo et al., 2019).

By using only the modal split module and introducing the outcome of the distribution module as an input, the influence of the changing parameters on the distribution of the freight was neglected. This results in that the possible economic impact was not taken into account in the study, which could be significant. Next to that, the distance price excluding the carbon price of road using diesel and BEVs has been kept the same in the BasGoed model. In reality, the prices will differ as fuel prices and maintenance to the trucks differ.

The results of the BasGoed model show that the choice of modes is not influenced much by the introduced carbon price. This is in line with Blinge (2014), stating that the freight transport system is very robust resulting in no drastic changes due to a CO_2 tax. Next to the little sensitivity to the cost changes, this small shift can be explained by the fact that for many zones in BasGoed there is no availability for IWW or rail. This results in no possibility to shift to other modes. Even though other studies that focused on container transport in the Netherlands found a larger shift between the modes (Zhang et al., 2014; Zhang et al, 2015), this difference can be explained logically by the fact that this research focuses on all the commodities of the transport in the Netherlands.

The resulting reduction in emissions increases gradually, which is mainly due to the increase in efficiency of the conventional diesel vehicles (as the sensitivity analysis shows). However, the total system cost increases as well. This can decrease the demand for freight transportation (Beuthe et al., 2013) which is not considered in this research but can impact the whole economy of the Netherlands.

This study has focused on the three areas explained above. However, the carbon price can influence many other fields. For example: technological innovation might be stimulated, extra infrastructure investments might be done and changes is the economy might occur. These fields could in their turn be an influence to the results that were found in this research.

5.2 Conclusions

The future of the transportation and energy sectors depend on hardly predictable technological progress, market developments and policy issues. This makes it hard to make predictions about the future. Nonetheless, this study has resulted in some final conclusions.

Introducing a carbon price affects several areas of freight transport in the Netherlands. First of all, the CO_2 emissions of conventional diesel vehicles decreases as investing in new reduction technologies is rewarded. Next to that, electric freight vehicles become a price-attractive option for the road mode, resulting in a decrease of emissions of the most unsustainable and most used mode. Furthermore, a slight modal shift occurs in which larger distances switch more to the sustainable modes than smaller distances. However, due to that the effect on the modal split is little, the decrease in CO_2 emissions caused by a modal shift is found to be little.

The effect that has the most influence on the reduction in emissions is the improvement of the technologies for the conventional diesel vehicles and the fuelswitch-effect. Furthermore, when the carbon price makes BEVs an economically viable option, this results in a reverse modal shift; using the road becomes cheaper and more attractive. As BEVs have few emissions, this leads to an accelerated decrease of the CO_2 emissions.

However, it should be taken into account that the introduction of a CO_2 price leads to an increase in the total system price. It was found that this increase is only due to the carbon tax and not due to the costs of the transportation itself. The impact of the increase in the total system price should be taken into account.

It is important to mention that these results should not be interpreted as what would happen in the future. Rather, the results of this study give an idea of what the effects of carbon pricing could be and how this is related to the CO_2 emissions of the freight transportation in the Netherlands.

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