Reducing CO_2-emissions of container transport in the Netherlands

An ex-ante evaluation of CO_2-emission reducing policy for container transport in the Netherlands, with a GIS-based model that uses detailed characteristics of modes.

Master Thesis, Final Draft

Martijn van den Driest
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Student:	Martijn van den Driest
Student nr.	1148079
E-mail:	martijnvandendriest@gmail.com

Delft University of Technology
Transport, Infrastructure and Logistics

Supervisors:

Prof. Dr. Ir. L. Tavasszy	TU Delft / TNO
Dr. B. Wiegmans	TU Delft / OTB
Dr. J.C. van Ham	TU Delft
Ir. R.G. Hekkenberg	TU Delft

Preface

During the course SPM9400, Design and Management of multi modal logistic chains, I got introduced to modelling intermodal container transport. The level of detail in the course was rather limited and I was interested to learn more about the topic, the idea for my master thesis was born.

Via prof. dr. Tavasszy I was introduced to Mo Zhang, PhD student at the OTB Research Institute. Her thesis is part of a research called 'Duurzame Bereikbaarheid Randstad' and she supplied the following challenge:

For the current environmental problems, environmental constrains have to be introduced to the transport system. The policy makers are looking for good solutions to limit the emission but not to impact the volume of freight transport in a negative way. Tax, subsidy, limitation, quotation, etc. Could be potential policies. The student is expected to design several policies and compare the impacts of each policy on the network flow in a GIS based simulating model. Cost analysis could also be a part of the assignment.

The OTB research institute provided the facilities to take this challenge, and halfway the project, TNO provided the facilities to do the calculations.

I am thankful to everybody that provided me with knowledge, input and comments to fulfil this thesis, especially my girlfriend, my supervisors, the people at OTB and TNO, Mo Zhang and the helpdesk of OmniTRANS.

Summary

The reduction of CO_2-emissions is one of the most important topics of plans and goals about climate change. A particular source of CO_2-emissions, the transport sector, needs to reduce its emissions as well. One of the options to achieve a reduction of CO_2-emissions, is to introduce a pricing system that causes a modal shift towards modes that have lower CO_2-emissions: rail and inland waterway transport. This way, a large reduction could be achieved by re-arranging the intermodal transport chains that are used to transport containers. Intermodal transport is defined as "The movement of goods in one and the same loading unit or vehicle, which uses successively several modes of transport without handling the goods themselves in changing modes".

Intermodal container transport is done with three transport modes, road, rail and inland waterway. The door to door costs are the most important parameter that influences the choice between those modes. Combining the cheap transport of inland waterway with the flexibility of road transport to deliver at any possible place leads to transport chains that are cost effective. Downside of intermodal transport is that it is often difficult to arrange the transport in such a way that the arrival time can be arranged in a small window.

The container transport market contains four main actors: the shippers, that initiates the transport by buying or selling a product to a client in a different location; the transporters, companies that can arrange the required service; the carriers, companies that actually transport the containers; and the terminals, that have the primary function to connect the legs of the different carriers to each other. The shippers form the demand side of the market; the other three are the supply side. Besides the actors in the market, the container transport network consists of two more things, the infrastructure network and the terminals.

As long as the vehicles that are used in container transport use fossil fuel or other hydrocarbons, there will be CO_2-emissions caused by the transport. Using 'green' electricity for trains could be a solution, however not all containers can be transported by rail. Road transport will always be necessary and at the moment, the emissions are 4 to 5 times higher than the emissions of rail and inland waterway transport. Reducing the share of road transport in the modal split will therefore lead to a reduction of the emissions.

CO_2-emissions of container transport modes

In this research, the Emissiescan of CE Delft is used to calculate the emissions of the transport means. Based on the fuel consumption, amount of vehicle kilometres, transported TEU's and the loading degree, the emissions are calculated. For road transport this results in 787,8 gram of CO_2 for each TEU-kilometer, for electrical rail transport this is 177,4 gram. Looking at inland waterway transport, the fuel consumption is highly dependent on the operational area of the ship. There is a large difference between sailing on deep parts of the IJsselmeer and sailing upstream on a shallow part of the Rhine. Therefore, the fuel consumption of five ship sizes; the CEMT classes II, III, IV, Va and VIb; have been calculated for three different water depths. This is done with the methods of Holtrop & Mennen and Karpov. This results in CO_2-emissions between 246 and 129 gram per TEU-kilometer at the average speed on medium deep water. Besides the emissions of the transport part of intermodal transport, the transhipments at terminals cause emissions as well. This varies between 4 and 13 kilos per transhipment.

One of the options to reduce the share of road transport is to make it more expensive. However, there needs to be a clear reasoning behind that. Pricing the CO_2-emissions of road, rail and inland waterway transport by means of a tax on energy consumption leads to a cost function that depends on the emissions of the carrier as well. The cost increase of road transport will be larger than the cost increase of rail and inland waterway transport. On average, the shippers will then choose transport chains that have lower emissions, simply because those chains are less expensive.

Building a container transport model

Changing costs by pricing emissions or regulating the use of different fuel sources in a competitive market will always lead to changes in the demand for transport of specific modes. In economics, this change in demand as a result of a change in costs or price, is expressed as the elasticity of the demand. However, in all available sources, cost changes in one single mode are used to calculate the elasticity of the mode and the cross elasticity of the other available modes. This works in evaluations of policy that involves changes in the costs of one single mode, but not for evaluations of cost changes of all modes at the same time.

The use of an intermodal container transport model makes it possible to calculate the effects of different emission reducing policies. Since such a model is not available, it is build for the purpose of this research. The structure of the model is shown in the next table.

Input	*Fixed part:* The fixed input of the model consists of the infrastructure networks, an origin-destination matrix with the container and the costs and emissions of the modes.
	Variable part: The changes in the costs and emissions of the modes, as a result of the different policy alternatives, are the variable input of the model.
Process	*Calculating likely routes:* The model starts by calculating a set of most likely routes for every origin-destination pair. These routes can be unimodal (e.g. direct road transport) or intermodal.
	Assigning the flows to the network: Based on the difference in costs of the most likely routes, a part of the flow between an origin and destination is assigned to a route.
Output	With the flows assigned to the network, it is possible to produce outputs like maps of the network use, transhipment numbers at the terminals, modal split data, total costs and total emissions.

The input of the model

The fixed part of the input consists of the networks, transport flows and the costs and emissions of the modes. The road-, rail- and inland waterway network are taken from ArcGIS-shapefiles supplied by TNO. The networks have been altered to reduce the number of links, which saves calculation time. The constructed origin-destination matrix of the container flows is based on a database supplied by the CBS. The model uses a cost function that is dependent on the distance, time, number of transhipments and the amount of emissions. The division between time and distance dependent costs makes it possible to handle differences in speed on different types of roads. The costs of road, €0,2758 per TEU-km plus €30,98 per TEU-hour, and rail transport, €0,06347 per TEU-km plus €7,54 per TEU-hour, are derived from reports of NEA, for the costs of inland waterway transport a different approach is taken. Based on the fuel consumption that is calculated to estimate the CO_2-emissions, the distance related costs per TEU-km are for a Class II ship €0,0722, for a Class III ship €0,0433, for a Class IV ship for a €0,0383, for a Class Va ship €0,0213 and for a Class VIb ship €0,0337. The time related costs consist of the labour, capital, maintenance and other costs. The labour costs are derived from the Collective Workers Agreement. The capital costs are estimated based on the new build value of the ship, the financing structure and the average age of ships in the specific class. The maintenance and other costs are assumed to be 1,5% of the new build value of the ship. Combining the four components with the total sailing hours of a ship in a year and its occupancy rate, the time dependent costs per TEU-hour are €1,100 for a class II ship; €0,8493 for a class III ship; €0,6938 for a class IV ship; €0,6122 for a class Va ship and €0,5165 for a class VIb ship. On top of these costs, a value of time of the freight in the containers is used as well. These values represent the value a shipper gives to the transport time. On average this is €11,02 per TEU-hour for road transport, €4,02 for rail transport and €0,05 for inland waterway transport.

The variable part of the input consists of the different policy scenarios. Three different groups are used: pricing the emissions, increase the use of biodiesel and changing the network. In the first group, all carriers have to pay an extra tax on energy consumption. The amount of tax is based on the CO_2-emissions per TEU-km and the CO_2 price in € per ton. The CO_2 price is varied between 10 and 200 € per ton. The second group is dominated by regulating the use of different mixtures of biodiesel in road and inland waterway transport. This increases the costs of the fuel but reduces the emissions. Besides that, pricing the emissions is investigated as well. The last group consists of adding a rail terminal in Valburg and a inland waterway terminal near Alblasserdam.

The processes in the model

Before the process of calculating likely routes and assigning the flows to the network can be described, a couple of general assumptions need to be stated.

- The shipper makes route and mode choices for every single container, in practice shippers often make such choices once a year for large batches of containers
- The route and mode choice is based on costs instead of price, the margins are assumed to be that small that costs are on average very close to the market prices
- Once the route and mode choice is made, it is possible to use it
- An increase in transport costs does not lead to less transport demand
- The origins and destinations are the production and consumption locations, which results in the absence of transport within the regions
- There is no difference between empty and loaded containers
- There are no empty trucks/trains/ships on the return leg
- Occupancy rates of carriers do not change

The model is built in the public transport class of OmniTRANS. This class uses an access and egress mode, walking or car by default, to connect the origin and destination to the public transport network, that consists of bus, tram and train by default. The infrastructure network consists of connector links from each centroid to the road or walk links, a road network and a rail network. The service network is modelled by various transit lines, each with their own mode, speed, frequency and many more properties. In a normal public transport model, the lines are designed with a specific goal, but in this case, the lines are constructed in such a way that the complete infrastructure network is covered. Translating public transport network modelling possibilities into a container transport model does not require major changes. The container takes the position of the passenger and the container needs to be transported along the route with the lowest generalised costs. The modes need to be translated as well. The rail and inland waterway modes are the transit modes, road transport is the walk mode. This way, it is possible to do a simultaneous route and mode choice. The road transport is modelled as the walk mode to use the OmniTRANS feature to look for "walk-only" paths as well, something it cannot do for vehicle transport.

The process part is split in two parts, it first calculates a set of most likely routes by comparing the costs of all alternatives; the second step is the assignment of the flow to the set of likely routes. An important part of both procedures is the use of a logit function to make choices between alternatives. In the route calculation, the probability of boarding lines is calculated based on the difference in costs of the alternatives. In the assignment procedure, the flows are assigned to the set of routes using the same logit function, based on the costs of the alternatives.

Calibration and validation of the model

Calibrating and validating the model is done in three steps. As a start the modal split of the model is compared to actual modal split figures. This required changes in the logit parameters and speeds on the road network to match it and resulted in a modal split of 69,6% road, 4,6% rail and 25,8% inland waterway transport. The second step to calibrate the model is done by comparing the modelled transhipment numbers of 16 terminals to actual transhipment numbers. By changing the transhipment costs of the terminals separately, the modelled transhipment numbers are within 20% of the actual numbers. The transhipment costs now varied between €17,50 and €90 per TEU. The third step is validating the model by comparing the sensitivity of the model to changes in the cost functions to sensitivities of other models and studies. This sensitivity results in demand elasticities and cross elasticities between cost changes and modal split share changes of the mode. The calculated elasticities are all in the same range as the elasticities found in literature. While calculating the elasticities, it became clear that there were quite some differences in the results when different changes in costs were used. It seems that the elasticities are not constant, which is caused by the occurrence of discreet steps in the modal split when the costs are increased or decreased.

The results

Pricing CO_2-emissions at rates between €10 and €200 showed that the large difference in CO_2-emissions of road, rail and inland waterway transport cause a change in modal split towards the modes with lower CO_2-emissions. However, when the price of a ton of CO_2-emissions is equal to the current price of CO_2-emission rights in the European Trading Scheme, which is around €15 per ton, the total amount of emissions goes down by only 1%. At higher prices, the effects are larger, at €200 per ton; the reduction of the total amount of emissions is 8,4%. As a result of the money that is spent on the emissions, the total transport costs increase by almost 10%. It can be concluded that pricing CO_2-emissions causes a decrease in total emissions and that the higher the price, the higher the reduction. It is also shown that the reduction of CO_2-emissions is almost the same as the reduction of containers that are transported by road. This is caused by the fact that almost 90% of the total emissions are caused by road transport.

This is also the reason of the larger effects of regulating the use of biodiesel in road transport on the total emissions. When road transport achieves a emission reduction of 20%, the total emissions go down by almost the same percentage. Since biodiesel is more expensive than normal diesel, the regulation causes a small modal shift as well, enlarging the total emission reduction. Using pure biodiesel has even more effect, using it in inland waterway transport as well could result in a emission reduction of 70%.

After looking at other options to reduce CO_2-emissions, by using biodiesel or making changes in the network, the following conclusion is drawn. Pricing CO_2-emissions leads to a more efficient use of the available container transport system, however, improving the CO_2-emissions of road transport leads to a larger reduction of the total emissions. The latter could be achieved by regulations that force road transport to use biodiesel, which has larger effects at lower costs.

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1. Introduction

Increasing road congestion is often seen as one of the drivers behind transport policy that aims for a modal shift from the road to rail or inland waterways. On a European level, the Marco Polo programs are examples of this (EU, 2007). On a national level, there have been numerous policies from the Dutch government to achieve a modal shift. Subsidies for rail or inland waterway connections, intermodal terminals and technical improvements are examples of policies that stimulate intermodal transport. The shift from direct road transport to intermodal transport has a potential cost benefit, although only when the distance is large enough.

The extra transhipment that is needed, costs additional time and money, therefore the transport itself needs to compensate by being cheaper per kilometre. This is possible since rail and inland waterway transport have significant economies of scale because on one hand the capacity of a train or inland ship is much higher than that of a truck. On the other hand the costs increase less than proportional to the increase in capacity. This does not only count for the direct transport costs, but the external effects, like congestion and CO_2-emissions, have the same benefits of scale as well.

Besides road congestion there is another driver for transport policies and that is climate change. Although the conclusions of the intergovernmental panel on climate change, the IPCC, proved to be subjective and sometimes even wrong in the last months, it is clear that emissions of greenhouse gasses (GHG) need to be limited. A good example of transport policy concerning GHG-emissions is the Euro-norm for road traffic.

To further increase the reduction of CO_2-emissions, the transport sector could be included into the Emission Trading Scheme of the European Union in the future, the timeframe for this measure is however still uncertain. At that point, the CO_2-emissions are no longer external effects, but will be included in the direct transport costs. This is a strong argument to internalise the costs in models that are used for the evaluation of recent and future transport policy.

Looking at the Netherlands, there are a couple of policy evaluation examples, like the intermediate evaluation of the 'Subsidieregeling Openbare Inland Terminals' (Decisio BV, 2002) and ECORYS (K.T.H. Vervoort *et al.*, 2005). Both use transport models to assess the effects of the policy. Some of these intermodal transport network models for the evaluation of transport policy are based on average costs and greenhouse gas emissions of the modes used for the transport. A large truck has the same costs per ton as a small one; a 6 barge push-barge combination has the same emissions per ton as a so called "spits", the smallest inland vessel. This might be valid for general models, but at a more detailed level this cannot be right.

1.1. Background of CO_2-emission reduction

In December 1997, the United Nations Framework Convention on Climate Change made a binding agreement on the reduction of greenhouse gas emissions, the Kyoto Protocol (UNFCCC, 1997). In total, 37 countries signed the agreement and are obliged to the reduction that is stated in the protocol. On average this results in a reduction of 5,2%, for the Netherlands this is 8%. These reductions need to be achieved in the period from 2008-2012 and are compared against the level of emissions in 1990. On top of the Kyoto Protocol, the European Union has set stronger goals in their regulation: a reduction of CO_2-emissions of 30% by 2030 (VROM, 2009).

Looking at container transport in the Netherlands, it can be concluded that the CO_2-emissions of the sector are a small part of the total emissions in the Netherlands. The complete transport sector is responsible for 17,4% of the CO_2-emissions (CBS, 2010). Container transport takes a rather small part of the total transport sector, around 10%. This shows that a reduction of CO_2-emissions in container transport alone does not really help, the goal of the European Union will only be achieved when all sectors reduce their emissions.

In general, the reduction in container transport could be achieved in two ways. Since inland ships and trains have lower emissions than a truck, a modal shift towards intermodal inland waterway or rail transport leads to a reduction of the emissions. This could be achieved by changing the relative cost differences between the modes in such a way that intermodal transport becomes more favourable. The other way does not require a modal shift, it focuses on reducing the emissions of each specific mode. This could be achieved by more efficient engines, fuels with less emissions (e.g. biodiesel or LNG) or by increasing the occupancy rates of the trucks, trains or ships. Increasing the occupancy rate could, for example, be achieved by reducing the number of 'empty' kilometres of a truck.

The three most important instruments to influence a market are regulations, changes in behaviour and financial benefits or penalties. Regulations are an instrument that pushes a market to develop itself in a certain direction. An example is the Euro norm for exhaust gasses of trucks, it is likely that truck manufacturers only invest in better engines when they are forced to do so. Some manufacturers will try to be the best in the market and put more effort in it than others, but in general one could argue that it is done from a marketing point to gain more clients. Changing behaviour of people or decision-makers does not necessarily involve laws or regulations, marketing campaigns could do the job as well. An example is the 'Het nieuwe rijden' campaign of the Dutch government. Advertisements and education is offered to the public to increase peoples' awareness of their driving style. Financial benefits or penalties can work two ways, a positive development could be awarded by a subsidy and no or negative development could be penalised by taxing. For example the tax discount on cars that have a better than average label and a penalty on cars that perform worse than average.

Since the transport market is a highly competitive market, the focus of all companies will be on reducing costs. Therefore, changing the relative cost difference based on the emissions of the mode is a suitable solution to change choices in the market.

1.2. Methodology

Changing costs by pricing emissions or regulating the use of different fuel sources in a competitive market will always lead to changes in the demand for transport of specific modes. In economics, this change in demand as a result of a change in costs or price, is expressed as the elasticity of the demand. Various sources have been found that evaluated the elasticities (W. M. Abdelwahab, 1998; M Beuthe *et al.*, 2001; G P Geilenkirchen *et al.*, 2010). However, all sources use cost changes in one single mode to calculate the elasticity of the mode and the cross elasticity of the other available modes. This works in evaluations of policy that involves changes in the costs of one single mode, but not for evaluations of cost changes of all modes at the same time.

Using an intermodal container transport model makes it possible to calculate the effects of different emission reducing policies. A classic method to model transport of passengers or freight is by means of a "4 step model" (P.H.L. Bovy *et al.*, 2006) that uses the following steps:

1. Trip generation that defines the number of departing and arriving trips in a region. This is often based on socio-economic or demographic factors.
2. Trip distribution that links the departing and arriving trips between regions. Usually this is done by a gravity model that takes a utility function into account to describe the costs or benefits to travel between a certain origin destination pair.
3. The mode that is used to travel is chosen in this step, often based on a logit function.
4. The route assignment is performed as a last step.

For this research, the results of step 2 are available so trip generation and distribution does not need to be performed. Another difficulty is that the mode and route choice are separate steps, while a key characteristic of intermodal transport is that those choices can be made at the same time. This requires a so called "simultaneous route and mode choice model" (P.H.L. Bovy *et al.*, 2006). Since such a model is not available, it is build for the purpose of this research. A brief structural overview of the model is shown in Table 1.1.

Table 1.1: Structural overview of the model

Input	*Fixed part:* The fixed input of the model consists of the infrastructure networks, an origin-destination matrix with the container flows between the regions and the costs and emissions of the modes.
	Variable part: The changes in the costs and emissions of the modes, as a result of the different policy alternatives, are the variable input of the model.
Process	*Calculating likely routes:* The model starts by calculating a set of most likely routes for every origin-destination pair. These routes can be unimodal (e.g. direct road transport) or intermodal.
	Assigning the flows to the network: Based on the difference in costs of the most likely routes, a part of the flow between an origin and destination is assigned to a route.
Output	With the flows assigned to the network, it is possible to produce outputs like maps of the network use, transhipment numbers at the terminals, modal split data, total costs and total emissions.

The inputs are found in literature, supplied by the Dutch Central Bureau of Statistics (CBS) or calculated based on other information. The process part is done by building the model in the public transit module of OmniTRANS, which can handle the assignment of intermodal routes.

1.3. Goal and research questions

In the introduction, two issues are addressed. The first one is related to transport policy, the possibility to introduce CO_2-emission pricing in the transport sector to decrease the amount of emissions. The second one is related to transport modelling; the problem that is introduced is the lack of detail in characteristics of the modes used in intermodal transport models. Combining the two issues leads to the goal to assess the effects of emission pricing with a model that takes differences within modes into account and is able to visualise the use of the network. The question that will be answered in this research is:

What are the effects of CO_2-emission reducing policy on container transport in the Netherlands?

To be able to answer the research question, the following sub-questions and goals are stated:

- *Build a GIS-based model to quantify, visualise and evaluate Dutch container transport.*
- *Differentiate the characteristics of the modes into more detail than is done in found policy evaluation.*
- *Identify, choose and evaluate a possible structure for emission pricing in the container transport sector.*
- *Identify and evaluate policy measures and developments that support the effects of CO_2-emission pricing.*

The first two goals are straight forward, obtaining sufficient data about characteristics of the modes, container flows and the network, combining that into a model and validating the results. The third goal is to identify different possibilities in emission pricing, mainly trading or taxation, which results in a structure that will be used in the model. The last goal is to elaborate on supporting measures, like subsidies for the conversion of equipment to make it suitable for bio-fuels.

1.4. Reading guide

This thesis starts with an overview of intermodal container transport. The characteristics, advantages and disadvantages, important decisive parameters and the current container transport in the Netherlands are addressed in chapter 0. The CO_2-emissions and pricing opportunities are addressed in chapter 3. Besides that, developments of technology that reduces CO_2-emissions of the modes are addressed as well. The last topic of chapter 3 is the definition of the scenarios that will be used in the model. To calculate the effects of pricing CO_2-emissions, a model is build and described in chapter 0. After the calibration and validation at the end of chapter 4, the results of the scenarios are presented in chapter 5. Finally, chapter 6 contains the conclusions, discussion and further recommendations.

2. Intermodal Transport

A lot of containers are transported by multiple modes when they are transported from an origin to a destination. Looking at the Netherlands, most of the inbound international containers that arrive in Rotterdam by a deep-sea vessel, are transhipped onto a truck, train or inland ship to be transported to the hinterland. The last leg of the transport chain is done by a truck that delivers the container at the final destination, somewhere in the Netherlands. This chapter starts with a brief introduction of the modes, continues with the advantages and disadvantages of intermodal transport and a description of the decisive parameters in the mode choice. The chapter ends with an overview of the current container transport in the Netherlands.

2.1. Modal characteristics

There are basically three possible modes in transport of containers: road, rail and inland waterway. All have specific characteristics like capacity, average speed, transport costs and external costs. Besides the modes, the container terminals are addressed as well. A terminal has a certain capacity in terms of handling speed and storage space and it also determines the costs of a single container transhipment. This paragraph will present an overview of the characteristics, with capacity in TEU per shipment, average speed in kilometres per hour and costs in € per TEU per kilometre. As a start, a qualitative overview of the characteristics of the modes, summarized by Platz (2009), is shown in table 2.1.

Table 2.1: Qualitative overview of modal characteristics, taken from (T.E. Platz, 2009)

	Feature	Road	Rail	Inland Waterway
Users				
1	Transport costs per unit	-	+	+
2	Ability to achieve the transport of large volumes	-	+	+
3	Transport speed	+	0	-
4	Network connectivity	+	0	-
5	Predictability of transport process	0	0	+
6	Transport frequency	0	0	0
7	Transport safety	-	+	+
8	Transport security	-	0	+
9	Convenience and flexibility	+	-	-
10	Resistance to extreme weather conditions	-	0	-
11	Limitation of infrastructure capacity, congestion	-	0	+
Governments				
A	Energy-use per ton-km	-	0	+
B	Emission of harmful substances	-	+	0
C	Emission of greenhouse gas	-	+	+
D	Noise, negative effects on ground and water	-	-	+

Legend: + relatively good performance, 0 medium performance, - weak performance.

It can be concluded from the table that road transport is the preferred option when speed, network connectivity and flexibility are the most important. Inland waterway gives the total opposite of that, as long as speed, connectivity and flexibility are not important, the performance is hard to match by the other two modes. A critical remark has to be made on the difference in performance on energy use per ton-km and the emission of greenhouse gasses. The performances in the table might be true when rail transport uses clean energy form the electrical power grid, when a train is using diesel traction, the performance will be different. In general, the table presents the difference in performance quite well. It should also be noted that the top eleven features are all considering direct effects for shippers or carriers, while the last four features are the interests of governments. This leads to different opinions about effects of policy between governments and the transport sector.

The following section elaborates on the modes in more detail, including the most important strengths and weaknesses. The most important characteristics are transport costs per unit, average transport speed and the capacity of a single carrier.

2.1.1. Characteristics of a truck

Road transportation is known for the ability to deliver at virtually any location, so it is very flexible. However, a downside is that a truck has a limited capacity per shipment, but that can be a benefit as well when a transport flow is not stable, small or consists of small shipment sizes.

Capacity

A truck is generally able to transport two TEU's, as long as the total weight of the truck and containers is lower than 50 tons. To reduce the number of trucks on the road, the Long Heavy Vehicle (LHV) or 'Eco-Combi' is developed (Arcadis, 2006).

Figure 2.1: An example of a LHV carrying three TEU's (www.combi-trailer.be, 2010)

After a successful pilot, the Eco-Combi is now allowed on the main road network through the Netherlands. During the pilot, the maximum allowed weight of the LHV was 60 tons, but now that is reduced to 50 tons.

Average speed

The speed of a truck is highly dependent on the location, type of road and amount of traffic on that road. One could argue that a truck driver that does not drive during peak hours will be able to achieve a driving speed of 80 km/hour, the maximum allowed speed. Due to regulations on driving times and congestion, the average speed of a truck between an origin and destination is significantly lower. Waiting times at terminals are also causing lower operational speeds for a truck. In 'Vergelijkingskader modaliteiten' (NEA, 2001), the average speeds of trucks in the Netherlands are 55 km/h for only national operating trucks and 68 km/h for trucks that also operate internationally. The difference is caused by the fact that internationally operating trucks cover larger distances for single trips, this reduces the effect of low speeds in urban areas.

Transport costs

The transport costs of a truck are depending on both time and distance, which could be aggregated to a value only depending on distance by dividing the time part by the average speed. The results of various sources are found in table 2.2, in € per TEU per kilometre.

Table 2.2: Road transport costs in €/TEU/km (Decisio BV, 2002; NEA, 2001; NEA, 2004)

Min	Max	Average	Costs level	Used in
0,54	1,17	0,90	2002	Evaluation of SOIT policy
		0,80	2002	Factorkosten van het goederenvervoer
		0,39	1999	Vergelijkingskader modaliteiten

The value from 'Vergelijkingskader modaliteiten' is low when compared to the other two. It is not clear what the cause of this difference is, however, the next two sections show similar deviations for the other two modes. An explanation could be that a different approach is taken to calculate the costs, but that is unlikely because both 'Factorkosten in het goederenvervoer' and 'Vergelijkingskader modaliteiten' are created by NEA.

Strengths and weaknesses

One of the most important factors in favour of road transport is that the available network of roads stretches from and to virtually every location one can think of, as long as it is not on an island. This does come with a price, so road transport is expensive.

Table 2.3: Strengths and weaknesses of road transport

Strengths	Weaknesses
- fast - flexible - no pre- and end-haulage needed	- expensive - small capacity - vulnerable to congestion

2.1.2. Characteristics of a freight train

Since a train requires a track to run on, the network of rail transport is bounded by the rail infrastructure network. This network is significantly smaller than the road network. According to information of the CBS, the Dutch rail network consists of 2155 km of electrified track and 741 km of un-electrified track in 2009, while the highway network consists of 5076 km roads (CBS, 2010).

Capacity

The capacity of the rail network is determined by two factors; the capacity of the tracks in terms of the amount of trains that can pass in a certain time span, and the capacity of the train itself. The capacity of the tracks is usually given in a number of available train-paths between an origin and destination, which consists of successively available track sections. At this point it is important to understand that freight transport uses the same tracks as the passenger transport services, which have priority in the Netherlands. The other capacity determining factor is the capacity of the train itself. According to Rail Cargo Information Netherlands, a container train with a maximum length of 650m can carry between 70 and 90 TEU's, depending on the amount of traction and weight of the containers (railcargo.nl, 2010). The occupancy rate of the trains is however uncertain.

Average speed

According to (NEA, 2001), the average speed of a container freight train is 50 km/h. There is however a large spread around that speed since rail freight transport in the Netherlands always interferes with passenger transport, except on the dedicated freight track: the Betuwelijn. The fact that passenger transport is preferred by the track owners results in a low speed, according to the White Paper on Transport of the European Union this speed is 19 km/h (European Commission, 2001). Another cause of the low speed is that trains often have to change locomotives at the border.

Transport costs

A few sources have been found that show the costs per container per kilometre. Table 2.4 shows the data of rail transport costs in € per TEU per km.

Table 2.4: Rail transport costs in €/TEU/km (Decisio BV, 2002; NEA, 2001; NEA, 2004)

Min	Max	Average	Costs level	Used in
0,16	0,16	0,16	2002	Evaluation of SOIT policy
		0,30	2002	Factorkosten van het goederenvervoer
		0,17	1999	Vergelijkingskader modaliteiten

Strengths and weaknesses

Rail freight transport in the Netherlands has one major weakness; the rail network is already used a lot by passenger transport, which leaves only a limited amount of train-paths available for freight trains. Due to this preference of the network owner, it is very difficult to increase freight transport by rail inside the Netherlands. For international rail traffic there are additional problems, like incompatibilities in the power infrastructure along the tracks and different safety systems. These are however not really important for this research, since it focuses on transport in the Netherlands. An overview is presented in table 2.5.

Table 2.5: Strengths and weaknesses of rail transport (B Wiegmans *et al.*, 2007)

Strengths	Weaknesses
- Safe - Low damage to the environment - Efficient use of energy per transported ton - Cheap on longer door-to-door connections	- Not flexible - Low reliability - Slow - Problematic access to local facilities - Low amount of train paths available

2.1.3. Characteristics of an inland ship

Inland ships come in different appearances, from a small vessel to a very large push-barge convoy. The Conférence Européenne de Ministres de Transport (CEMT) has made a distinction in ship types, so called classes (CEMT, 1992). The network of inland waterways determines the maximum size, or class, of the ship that is able or allowed to sail on a certain link.

Capacity

A lot of general cargo or bulk carrying inland ships are also suitable for the transport of containers. This is possible because an inland ship is generally box-shaped and therefore it has a box shape cargo hold, which creates possibilities for containers. There are some examples of dedicated containerships, like the Neo-Kempenaar (Mercurius Group, 2009) and the JOWI-class (F van Zeijl, 1999). General inland ships have a certain capacity but it is not valid to divide that capacity by the average weight of a container to give the capacity in TEU's. The actual dimensions and capacities of the classes are stated in table 2.6.

Table 2.6: Classes of inland ships, combined from (BVB, 1992; DLD, 2003)

Class	Standard, single hull ship					
	Type	Length	Breadth	Draught	Capacity	Capacity
		m	m	m	Ton	TEU
0	Small	-	-	-	<250	Not available
I	Spits	38,5	5,05	1,8-2,2	250-400	Not used
II	Kempenaar	50-55	6,60	2,50	400-650	24
III	Dortmund – Eemscanalship	67-80	8,20	2,50	650-1000	48
IV	Rijn – Hernecanalship	80-85	9,50	2,50	1000-1500	90-120
Va	Large Rhineship	95-110	11,40	2,50-2,80	1500-3000	120-208
VIb	JOWI	135	16,8	3,9	4500	398-470

The two smallest classes are not suitable for the transport of containers, class 0 are recreational vessels and class I is not wide enough to suit more than one container next to each other.

Average speed

The average speed of inland ships is rather low. The maximum speed on the large rivers and canals is 18km/h through the water; on a lot of smaller waterways the speed is limited even further. Besides legal speed limits, bridges and locks are also causing lower average speeds. On the Rhine this is not an issue, but on the all the other waterways in the Netherlands there are a lot of bridges that need to be opened or locks that have to be passed.

Transport costs

The transport costs of an inland ship differ from the costs of a train or truck. The different classes of ships have different operational profiles and running costs, and therefore operational costs. A lot of researchers used models with an average value; these are shown in table 2.7.

Table 2.7: Inland shipping transport costs in €/TEU/km, (Decisio BV, 2002; NEA, 2001; NEA, 2004)

Min	Max	Average	Price level	Used in
0,08	0,29	0,19	2002	Evaluation of SOIT policy
		0,165	2002	Factorkosten van het goederenvervoer
		0,05	1999	Vergelijkingskader modaliteiten

The numbers in the report "Factorkosten van het goederenvervoer: een analyse van de ontwikkeling in de tijd" (NEA, 2004), are in € per ton per kilometre. Multiplying that with the average weight of a transported container of 10 tons (M van Schuylenburg *et al.*, 2001) results in the number in table 2.7.

Strengths and weaknesses

One of the major downsides of inland shipping is that it is slow, a problem which cannot be solved. Besides being slow, the network of inland waterways is not very dense, so pre and end haulage usually takes quite some distance as well. Positive about inland shipping is that a single ship can carry a lot of cargo and that the costs per container are very low.

Table 2.8: Strengths and Weaknesses of Inland Shipping, derived from (B Wiegmans, 2005)

Strengths	Weaknesses
- Sufficient infrastructure capacity - High level of safety - Less harmful to the environment - Reliable - Not expensive per TEU-km - Capable of carrying large volumes - High level of safety. - Less harmful to the environment	- Low speed - Not flexible - Low density of terminal network - High investments needed for new barges - Sea terminals favour deep-sea sector - Depending on natural constraints - Limited lock operating hours

As stated earlier, inland shipping is an alternative as long as speed and flexibility is not important.

2.1.4. Characteristics of a container terminal

To connect the different legs in an intermodal transport chain, the load unit needs to be transhipped at a certain location, the terminal. This is mostly done at dedicated terminals near the coast, connecting the deep-sea legs to the hinterland transport. If the hinterland transport is done by train or ship, an additional terminal is used in the hinterland, to tranship the container to a truck that does the final delivery or end haulage. Besides the actual transhipment, a lot of terminals provide services like cleaning, maintaining and storing of containers. The costs of the transhipment are very important in an intermodal chain and need to be minimised (B Wiegmans, 2003).

Transhipment costs

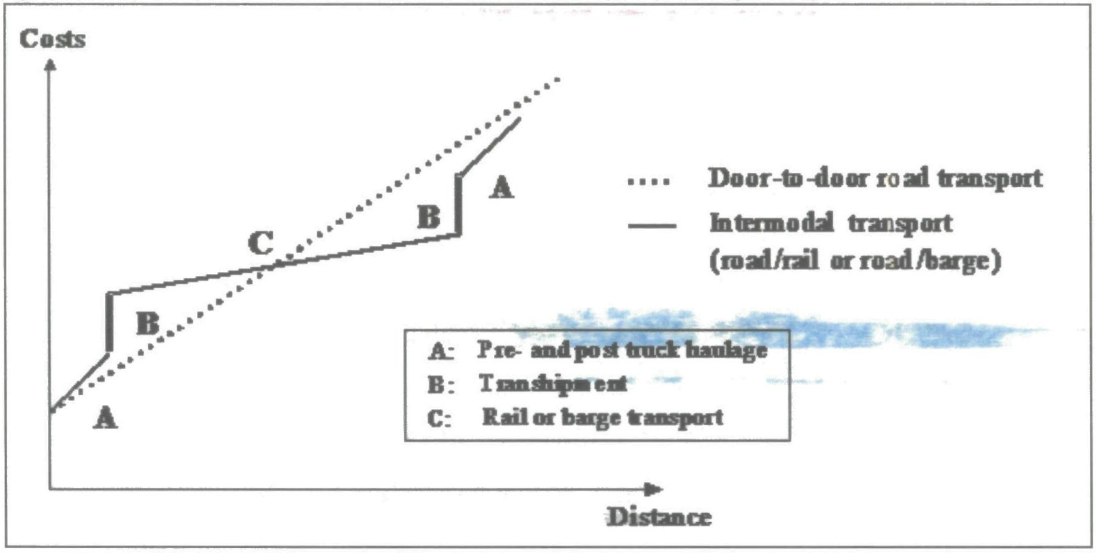
Sources to derive the transhipment costs of containers are very limited. One of the sources states that the costs vary between €14 and €68 per TEU in 2002 (Decisio BV, 2002) on inland terminals. Another source, from the Recordit research, states €30 per TEU in 2001 (M Savy, 2001).

2.2. Advantages and disadvantages of intermodal transport

Intermodal transport could be defined as using multiple modes for the transport of a certain good from its origin to its destination. The main motivation to do this is the possibility to combine the strengths of the separate modes into a streamlined transport chain, intermodal transport. There is however no clear and widely used definition of it, as is shown in a literature review of (Y M Bontekoning *et al.*, 2004). A total of nineteen slightly different definitions, used in other literature, are stated. Most of them contain only the physical characteristics of the transport, some include parts of the organisational structure and some state explicitly that the good itself does not change of load unit. This means that it is for example loaded into a container or trailer that is transhipped from one carrier to another. The definition of intermodal transport that will be used in this research is: "The movement of goods in one and the same loading unit or vehicle, which uses successively several modes of transport without handling the goods themselves in changing modes" as is used by the European Commission (ECMT, 1997). The organisational or service part that is mentioned by others is left out because intermodal transport is not depending on a specific type of organisation or service. There are a lot of alternative ways to organise an intermodal chain, without compromising to the definition that will be used.

The most important motivation to use intermodal transport is that it has lower costs than unimodal road transport. This is however only true when the distance that is travelled by rail or barge is large enough, since there are additional transhipment costs involved in an intermodal chain. Figure 2.2 shows an example of the costs of a transport chain, both of a uni- and an intermodal chain.

Figure 2.2: Cost comparison between inter- and unimodal transport (R Konings, 2009)



Intermodal transport is only possible when there is a sufficient amount of terminals, spread over the road, rail and inland waterway network. The locations of the terminals determine the place of transhipment and, since pre and end haulage is more expensive than normal road transport, it is important that the terminals are as close as possible to the origin and destination of the freight. From this perspective it seems ideal when there are a lot of terminals. There is however a certain amount of flow needed to operate a terminal cost efficient, so the amount of terminals in a given network is not unlimited. Focussing on the Netherlands, there are 38 inland shipping container terminals and 20 rail container terminals. Some of the terminals can handle both inland ships and trains (railcargo.nl, 2009).

Downsides of intermodal transport are that it is slower than road transport and that it is very difficult to organise an intermodal chain in such a way that the arrival time can be arranged in a small window. According to 'Transport en Logistiek Nederland', these are the most important reasons not to choose intermodal transport (TLN, 2007).

2.3. Decisive parameters in the mode choice

There are a couple of parameters that are important when a shipper or customer has to choose a certain transport solution. According to Kreutzberger, unimodal transport always acts as a reference case. Shippers always compare the door-to-door costs and time, service frequency, departure and arrival times, reliability, flexibility, shipment restrictions and the possibility to send partial loads. The door-to-door costs are the most important parameter, but there are situations where time or quality has the priority (E.D. Kreutzberger, 2008).

Besides the actual time that a door-to-door transport takes, the time also represents a certain value. Transport costs are not only depending on the distance, costs like wages of a driver are independent of distance but directly related to the time the transport takes. Another time dependent cost factor is related to the value of the freight that is transported. Investing the value of a good in a different way results in interest income and on the other side, the money invested in a good costs interest as well. Depreciation might be important as well, saving transport time enables the owner of the good to sell earlier, saving some depreciation. These three aspects show that transport time has a value that needs to be assessed.

Research by RAND has valued transport time, from a shippers point of view, for the Dutch Ministry of Transport, in order to evaluate infrastructure projects more accurate (G. de Jong *et al.*, 2004). The values are categorised into the transport mode and are in € per TEU per hour, at the price level of 2002. The next table shows the results, the values are a measure for the part of the transport costs that is time dependent, like wages of a driver and the value of time of the freight that is transported. The value should be read as the change of the transport costs when the transport is faster or slower; one hour less means a cost decrease of €42 per TEU for a truck.

Table 2.9: Time dependent part of transport costs, in € per TEU per hour

Mode	Road	Rail	IWW	Sea
Transport costs that are time dependent (€/TEU-hour)	42	11,56	0,542	0,176

It is obvious that road transport is much more expensive than the other modes, which is caused by the limited capacity of a truck and the fact that most goods that devaluate quickly are transported by truck. All the factors that are not related to the direct transport costs can be identified as a specific quality of the mode. A faster, more accurate or more reliable mode has a higher perceived quality than a slower mode. This is also valid within a mode when services of different carriers are compared.

2.4. Current container transport in the Netherlands

This paragraph will elaborate on the Dutch container transport market. First, a couple of definitions are stated to name the actors that are active in the market. After that, the network is discussed, the origins and destinations and the available infrastructure. In the sections that discuss the network, choices will be made to support the transport model that will be built in chapter 0. The final section shows a general overview of the container flows in the Netherlands and the construction of the origin destination matrix that will be used in the model.

2.4.1. Actors in the container transport market

A lot of actors are involved in the transport market. The following list shows a selection of terms or definitions that are often referred to as actors in a transport chain. The list only contains four actors: the person or company that owns a good that needs to be transported to another location, the company that can arrange the transport and the company that actually transports the product, the fourth actor is able to tranship the load unit of the transport.

Table 2.10: Overview of the actors in the container transport market

Shipper	The actor that is named as the initiator of the transport. This can be the buyer or seller of a certain product that needs to be transported, or a company that has to transport their intermediate product to a different assembly location (T G Crainic *et al.*, 1996). An example of a buyer being the shipper is when a product is sold "ex-works" and the buyer has to arrange the transport to the desired location himself.
Transporter or forwarder	A logistical service provider that can arrange everything that is needed for the transport of a shipment, its clients are the shippers. It can consolidate smaller sized packages or batches into larger batches. In case of intermodal transport, the forwarder chooses the carriers and therefore the modes, and makes sure that all parts of the route are connected to each other. (R Hellberg, Sannes, R, 1991)
Carrier	Companies that transport the freight with own or hired equipment. These are the trucking companies, train operators and shipping companies that deliver the container from origin to destination (T G Crainic *et al.*, 1996).
Terminal operator	The companies that can tranship containers between different carriers. Besides this primary task, the terminals also supply other services like storage and maintenance of containers.

It is not necessary that a transport chain contains all four actors. Sometimes the shipper has good contacts with a specific carrier and arranges the transport without a forwarder. This way the forwarder is more or less included in either the shipper or the carrier, which depends on the type of contract. Some literature (T G Crainic *et al.*, 1996) even states that a freight forwarder or a broker are examples of shippers. Others, like (J.L. Tongzon, 2009), divide shippers into three categories, one that uses long term contracts with selected carriers, one that use freight forwarders and a group that has its own transport equipment. The demand and supply side of the market can be recognised in the overview as well. The shippers create the transport demand, with their own specific needs like maximum transport price and time. The transporters, carriers and terminals are on the supply side of the container transport market. They can fulfil the demand of the shippers and have their own characteristics.

There are a lot of different organisational structures in a transport chain with their own division of responsibilities to actors, but all of them at least contain the tasks and characteristics described in the list. The different structures have influence on the decisive parameters of the previous paragraph. The route choice, and sometimes even the mode choice, is made by a certain actor: the shipper, the transporter or the driver of the carrier (G. de Jong *et al.*, 2003). The research of De Jong concludes that the shipper determines the route in 20% of the cases, the transporter in 50% and the driver in 30%. The research is however limited to companies that mainly use direct road transport. It is likely that the route choice in intermodal transport has more or less the same distribution for the separate legs. It is however unlikely that the mode choice is distributed in the same way, especially since the driver of one of the carriers that is used cannot make choices independent of the other carriers' drivers. The mode choice will be made by either the shipper or transporter. If the shipper makes the choice, the value of time of the freight in the container will influence the choice directly and the shipper chooses the route with the lowest logistical costs. When the transporter chooses the modes, the value of time is less important. The mode and route choice will not only be based on the interests of the client, the interests of the transporter are more important and the choices will be in favour of transporter, as long as the demands of the client are satisfied. One of the demands of the client will be the maximum time the transport takes, which influences the money that is spend on the value of time. It is assumed that this results in shippers that determine the route and mode, even though the control is not always direct. It can therefore be concluded that value of time needs to be included in the model.

2.4.2. Origins and destinations

Being dependent on the level of statistical information for the transport flows, it makes sense to use the statistical regions as origins and destinations. The available statistical information is a database of the CBS, which has a NUTS level 3 division of regions inside the Netherlands. These regions are also known as COROP-areas, chosen by the CBS in 1971 and never changed to keep statistics consistent. Since the infrastructure networks have a lot of links through the regions, a point has to be chosen in the region that acts as the origin or destination of the containers. This point is called a centroid and is placed in the largest city or most important area of the region.

Since the Netherlands is a country that is also commonly used for the transport of freight to and from other countries, some more regions need to be included in the model that will be built. The level of detail can be decreased, because it makes the model unnecessary large when all Western Europe is included at NUTS 3 level. A total of 18 areas outside the Netherlands are chosen in five countries, based on the number of containers that are transported to those regions. It is assumed that most of the transport to other European countries is done by short sea shipping.

Table 2.11: Overview of the areas outside the Netherlands

Country	Number of areas	Main region
Belgium	7	Antwerp
Germany	7	Ruhr
France	2	North
Italy	1	North
Poland	1	

A map of the chosen areas, including the Netherlands, is available in Appendix I.

2.4.3. The container transport network

An intermodal transport network consists of three parts, the infrastructure like roads and railways, the terminals that connect the different infrastructure networks, and the services that are provided by transporters. For this research, it is assumed that services are available between each terminal.

The infrastructure networks in the Netherlands

The most important roads in the highway network of the Netherlands are the six east to west (the A7, A2, A12, A15, A58 and A59) and four north to south (the A7/A4, A27/A6, A2 and A73/A50/A28) connections. Around the cities of Amsterdam, Utrecht, Rotterdam and Nijmegen, the network is denser to provide additional accessibility. The total highway network stretches 5076 kilometres (CBS, 2010). The highway network is complemented by the main local roads, that have a total length of 7745 kilometres (CBS, 2010). A map of the combined network that is used in the model is available in Appendix II.

The network of railways has a similar appearance as the road network, four east to west (one of them is the Betuwelijn, a dedicated freight track) and four north to south connections. The network can be divided into three types of allowances and two types of traction. The allowances are passenger only; passenger and freight and freight only; the types of traction are diesel and electricity. A map of the railways is available in Appendix III, however, the map does not specify the type or allowance on the track.

The last network is the inland waterway network, which are dominated by a river and two canals. The most important river is the Waal that enters the country near Nijmegen and flows to Rotterdam. The important canals are the Amsterdam-Rijn Canal, which connects Amsterdam with the Waal to provide a connection to Germany, and the Schelde-Rijn Canal, that connects Rotterdam and Antwerp. These waterways are all navigable by the largest inland ships. A lot of other inland waterways exist, the total lengths of them is already stated in table 2.6. A map of all inland waterways in the Netherlands of class II or higher is available in Appendix IV.

The locations of the container terminals

The maps of the rail and inland waterway network in Appendix III and IV show the terminal locations as well. The locations are derived from a Google Earth file (railcargo.nl, 2009) that shows all intermodal freight terminals in Europe. The terminals that are not equipped to tranship containers were removed and some terminals were combined. A list of the container terminals, including their number in the model, the transhipment costs and the pre and end haulage distances is found in Appendix V

2.4.4. Container transport flows in the Netherlands

This section will give a general overview of the container transport flows in the Netherlands. According to data of the CBS (CBS, 2010), around 1,6 billion tons of freight was transported to, from or through the Netherlands in 2003, the total of ton-km's was around 175 billion. Looking at containers, the largest flows are to and from Rotterdam. In 2006, almost 5 million TEU's arrived in the port of Rotterdam, while 4,7 million TEU's departed from the port (www.portofrotterdam.com, 2010). The same data shows that there is a ratio between the number of containers and the number of TEU's, 1,647. Some of the containers only stay in the port until they are transhipped to another sea-going vessel, but about 76% is transported to the hinterland. Table 2.12 shows the modal split of containers that are transhipped in the port of Rotterdam. The largest flows to the hinterland are in the direction of Germany and Belgium.

Table 2.12: Modal split of TEU's Rotterdam in 2006, from (www.portofrotterdam.com, 2010)

	TEU*1000	%	%
Total	9666		
Sea-sea transhipment	2305	23,9	
To hinterland	7360	76,1	
By road	4313		58,6
By rail	802		10,9
By inland waterway	2245		30,5

Another source shows modal split data for all container transport in the Netherlands. The interim evaluation of the SOIT-subsidy used a reference case with a modal split of 75.6% road, 4.4% rail and 20% inland waterway transport.

A database of the CBS provided numbers of container transported to or from the Netherlands. The database is processed into an origin-destination matrix with all the regions that were chosen in section 2.4.2. The containers that have their origin and destination in the same region are removed, since modelling the transport of these containers is not accurate. The only region where the transport within the region will be taken into account is Rotterdam, the region is split in a harbour and city area. Maps that show the number of containers in the origin-destination matrix are available in Appendix VI.

3. The CO_2-emissions and pricing scenarios

In the early 90's, Verhoef presented an article about the external effects and social costs of road transport (E Verhoef, 1994). It valued the social costs of congestion and the costs of greenhouse gas emissions as most important, and stated that the values for both are underestimated in previous research. This chapter will focus on the emissions of the modes used in container transport, the developments to reduce those emissions, possible structures to reduce the amount of emissions and concludes with scenarios that are used in the model that is build in Chapter 0. Since the CO_2-emissions of a carrier are highly related to the specific characteristics of the carrier, the modes are from now on divided into more means. This is done to increase the level of modal detail in the model later on. The means are shown in table 3.1.

Table 3.1: The division of the modes into means

Mode:	Road	Rail	Inland waterway
Means	Euro V	Diesel	Class II
	Euro VI	Electrical	Class III
	LHV		Class IV
			Class Va
			Class VIb

The road is divided into three categories. Two categories originate in the different EURO norms that are in force right now, EURO V, and will be in force in 2013, EURO VI. The difference will be small, but it is found in information of manufacturers that a EURO VI truck will emit more CO_2 than a EURO V truck does. This is caused by the lower burning temperature in the engine to reduce the emissions of particle matter and nitrogen-oxides. The lower temperature leads to a lower efficiency of the engine and therefore it uses more fuel and emits more CO_2. The third road mode is the Long Heavy Vehicle (LHV), better known as the eco-combi, a longer truck that is able to carry three TEU's. These trucks are however not allowed to drive everywhere, in the Netherlands they are allowed to drive on the highways and national roads. Other European countries are preparing similar rules, but it will take some years until an LHV can drive from Rotterdam to, for example, Italy.

Making a division in the rail sector is quite easy; there are simply two types of traction available, diesel or electrical locomotives. It is found that diesel traction is most used on short distances within a port area and that electrical traction is common on longer distances.

The inland ships are divided into the classes of waterways that exist, with the exemption that large push-barge convoys are not used in container transport. The details of the ships are represented earlier in Table 2.6, and will be further detailed in paragraph 4.1.3.

3.1. CO_2-emissions of road, rail and barge transport

Every engine that burns fossil fuel emits exhaust gas that contains CO_2. This is the result of burning hydrocarbons. So as long as oil or natural gas is used as a fuel for transport carriers, there will be CO_2-emissions caused by transport. This is where rail transport has a very large potential, running a freight train on electricity that is produced CO_2 neutral leads to a freight transport that has no emissions at all. In practice the CO_2 neutral electricity is too expensive to use for transport, but there has been a pilot project in Germany that used windmills as an energy source for a freight train. The following sections elaborate on the CO_2-emissions of the modes, which are derived from the Emissiescan of CE Delft (CE Delft, 2010). This program can calculate the emissions of a transport company based on:

- The mode that is used
- The fuel consumption of the mode
- The amount of vehicle kilometres
- The amount of TEU's
- The amount of TEU-km's
- Mode depending variables

To be able to tag a price on a certain amount of CO_2, the emissions will be given in grams/TEU-km. Since all carriers have varying loading degrees, the emissions will be corrected with the average loading degree found in (NEA, 2004) and estimated in section 4.1.3, shown in table 3.2

Table 3.2: Average loading degrees of the means (NEA, 2004)

Road		Rail		Inland waterway	
Mode	Loading degree	Mode	Loading degree	Mode	Loading degree
Euro V	48%	Diesel	90%	Class II	60%
Euro VI	48%	Electric	90%	Class III	70%
LHV	48%			Class IV	60%
				Class Va	80%
				Class VIb	90%

The loading degree of rail seems to be too high. This might be caused by the way of measuring the loading degree. If the percentage of used container spots is used, the loading degree might be high due to empty containers. Another way of measuring is using the transported weight and the capacity in terms of weight. This way, empty containers cause a significant decrease of the presented loading degree. It is however not clear how the figures are measured.

3.1.1. Road transport

In the Emissiescan, the following function is used to calculate the CO_2-emissions of a truck:

$$CO_{2,TRUCK,TOTAL} = \frac{CO_{2,perKM} + CO_{2,perLfuel} * fuelconsumption}{Capacity * loadingdegree}$$

The $CO_{2,perKM}$ and $CO_{2,perLfuel}$ are fixed variables, the fuel consumption, capacity and loading degree have to be defined. It should be noted that double counting seems to occur, however, the documentation of the Emissiescan states that this is not the case. The tool calculates the emissions of a complete year, with the amount of kilometres that are driven and the litres of fuel that are used. This is done to capture the effects of the truck waiting at a terminal or other location, with a running engine. The capacity is 2 TEU for the two normal trucks and 3 TEU for the LHV. The loading degree is stated in table 3.2. The fuel consumption is more difficult since it depends on the weather, type of tyres, vehicle load, driving style and conditions, the terrain and the quality of the fuel. The fuel consumption of the Euro V truck is the average of 11 trucks that were tested by TLN in the past two years. It is assumed that a Euro VI truck uses 1% more fuel. The fuel consumption of the LHV is derived from Arcadis (2006).

Table 3.3: CO_2-emissions of road transport (NEA, 2001)

	Euro V	Euro VI	LHV
Fuel consumption (l/100km)	28,8	29,1	40,1
CO_2-emissions (g/TEU-km)	787,8	791,6	664,1

3.1.2. Rail transport

The function that is used in the Emissiescan to calculate the CO_2-emissions of rail transport is based on different parameters than for road transport.

$$CO_{2,RAIL,TOTAL} = Energyconsumption\,[MJ/(TEU-km)] * CO_2[g/MJ] * loadingdegree$$

For both means, electrical and diesel traction, the first two values are stated and the loading degree follows from table 3.2.

Table 3.4: CO_2-emissions of rail transport

	Diesel	Electric
Energy consumption (MJ/TEU-km)	2,332	0,938
CO_2-emissions (g/MJ)	87,49	170,3
CO_2-emissions (g/TEU-km)	226,7	177,4

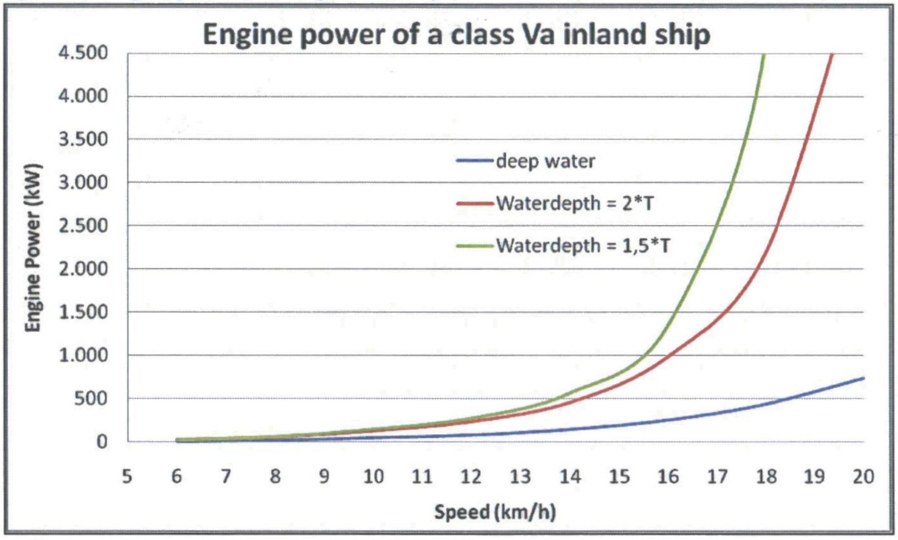
3.1.3. Inland waterway transport

For inland waterway transport, the same function is used as for rail transport.

$$CO_{2,IWW,TOTAL} = Energyconsumption\,[MJ/(TEU-km)] * CO_2[g/MJ] * loadingdegree$$

The energy consumption differs for different operational areas. Due to additional resistance in shallow water there is a lot of variability in the energy consumption of the different classes of inland ships. The loading degree is another very important factor when it comes to energy consumption. The used power and efficiency of the engines determine the fuel consumption and the caloric value of that fuel determines the energy consumption. The engine power can be calculated with the method of Holtrop & Mennen (J Holtrop *et al.*, 1982) for deep water, but needs to be corrected for the effects of shallow water with the method of Karpov (T. van Terwisga, 1989). This is done for a speed range between 6 and 20 km/h and three water depths, deep water, two times the draught of the ship and 1,5 times the draught of the ship. To illustrate the effects of shallow water on the resistance of a class Va ship, it is shown in figure 3.1.

Figure 3.1: Engine power of a Large Rhine Ship



The power requirements of all ship types and water depths are available in Appendix VII. With a specific fuel consumption of 215 g/kWh and caloric value of 42700KJ/kg, the energy consumptions can be calculated. The CO_2-emissions that are a result of the transport are shown in table 3.5.

Table 3.5: CO_2-emissions in [g/TEU-km] a, b and c are: deep water, 2*draft and 1,5*draft

	Class II			Class III			Class IV			Class Va			Class VIb		
Km/h	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
6	48,7	48,7	51,3	35,8	35,8	38,0	20,9	20,9	21,7	16,3	16,3	16,3	21,4	21,4	23,2
8	83,5	87,8	95,6	61,1	64,8	70,8	35,6	37,4	40,9	26,7	26,7	30,0	34,2	37,1	42,3
10	129	175	194	105	124	139	60,0	71,3	80,9	44,3	50,2	57,4	53,3	67,8	80,0
12	192	246	282	139	185	212	79,1	107	123	59,3	76,9	90,6	69,6	103	126
14	290	424	507	208	312	376	116	179	217	86,1	129	159	95	167	217
16	444	848	1165	314	600	797	174	343	459	126	244	333	133	308	444
18	689	1834	3686	478	1214	2362	266	697	1391	189	484	1017	190	597	1541

When these numbers are compared to road transport, it becomes clear that inland shipping is a very clean way of transporting containers, as long as the speeds are not very high on shallow water. In the previous years, legislation about the emissions of inland ships has been introduced. The CCR-norms work similar as the Euro-norms for trucks, the focus is on particle matter and nitrogen oxides and not on CO_2. A difference with the Euro-norms is that the carriers do not experience an increase in fuel consumption with a higher norm.

3.1.4. The emissions on a container-terminal

On a container terminal, a lot of equipment is used to take care of the required handlings. This equipment varies from a fork-lift on a small terminal to the very large quay-cranes and automated guided vehicles on the deep sea terminals of ECT. The emissions of the different types of equipment are found in (R van Duin *et al.*, 2008). The paper presents a model to calculate the emissions of a terminal, based on the layout, used equipment and container throughput.

Table 3.6: CO_2-emissions of terminal equipment

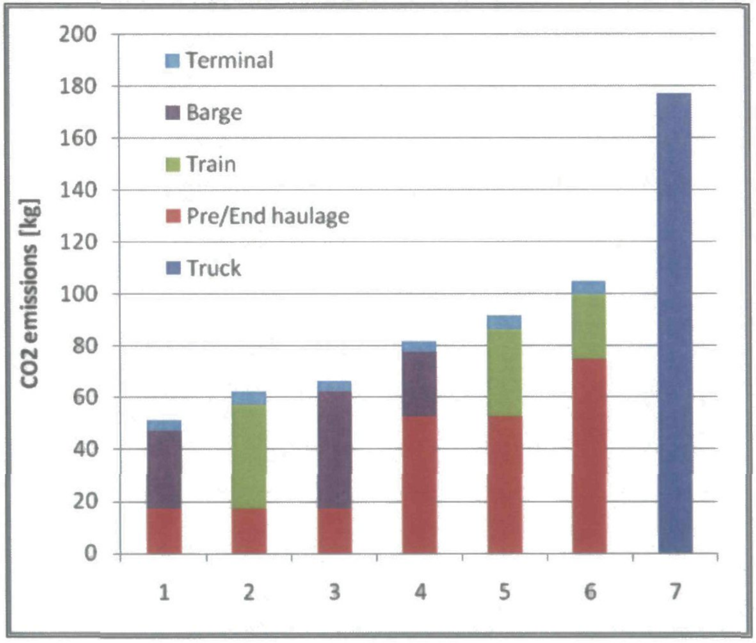
Equipment	Used for	CO_2-emission per container move [g]
Quay crane	Sea <-> terminal	3120
Barge crane	Barge <-> terminal	2080
Rail crane	Rail <-> terminal	2600
AGV + stacking crane	Stacking	8115
Straddle carrier	Road <-> terminal	2120

It should be noted that the emissions of stacking operations will be higher on a large deep-sea terminal than on an inland terminal. The paper does not present figures for inland terminals, but it is assumed that the stacking operation on a small inland terminal has negligible effects on the CO_2-emissions of that terminal. This leads to 13 kilos of CO_2 for transhipment from a deep-sea vessel to an inland barge and 4,2 kilos for a barge to truck transhipment.

3.1.5. A comparison of the modes

To show the differences in CO_2-emissions of the modes, an example route will be elaborated in this section. The CO_2-emissions of a container from the ECT Delta Terminal in Rotterdam to the city Heerlen are calculated for seven different routes, shown in figure 3.2.

Figure 3.2 Modal composition of CO_2-emissions of seven routes from Rotterdam to Heerlen



Route	Mode	Terminal used:
1	Va Ship	Born
2	Train	Born
3	II Ship	Born
4	Va Ship	Venlo
5	Train	Venlo
6	Train	Eindhoven
7	Truck	None

It is clearly visible that intermodal transport has much lower CO_2-emissions on a route from Rotterdam to Heerlen. It can also be concluded that the emissions of pre and end haulage have a lot of impact on the emissions of an intermodal route and that the terminal does not play a major role.

3.2. Difference in the developments of the modes

For all three modes numerous developments can be identified that lead to a decrease of the amount of CO_2-emissions. Some require extensive changes or are only possible on new vehicles; others can be installed in the existing fleet of a transporter. Important to keep in mind is that the reduction of CO_2-emissions can be achieved in two ways, one is to increase the efficiency of the carriers that are used; the other is to use the carriers more efficiently. An example of the first way is using an engine that has lower fuel consumption, while the second way can be achieved by arranging a transport chain differently to increase the loading degree of a carrier. The following lists show developments for each mode.

Road transport

- *Tires with less rolling resistance*
  Optimizing the design of the profile and the rubber compound of a tire can result in significant fuel savings. Downside is that reducing the rolling resistance of a tire is achieved by reducing the grip, which makes the tire a little less safe.
- *Spoilers and equipment that reduce air resistance*
  Closed sides and aerodynamically optimised shapes of the rear of trailers can reduce the air resistance. On containers this is difficult, since it has to be attached to the containers.
- *More efficient engines, although that is not achieved by Euro norms*
  Turbo or compressor charged engines, intercoolers, high pressure common rail systems and direct injection of fuel are all examples of developments that improved the performance of the diesel engine. All have more or less the same effect; they increase the temperature and pressure at which the fuel is burned. The higher these are, the higher the chance that all particles of fuel are burned. Downside is however that the nitrogen that is in the air also tends to bind on oxygen at very high pressures, which leads to extra emissions. This effect can be reduced by adding so called AdBlue, an additive that the driver needs to put in the diesel tank each time he stops at a gas-station.

Rail transport

- *Clean electrical energy as a source*
  The source of the electricity that powers the train has a lot of influence on the CO_2 performance of this mode. It is possible to run a train on “green” electricity, but the supply of that source is not large enough to use it on a large scale in rail transport.
- *Efficient routing that contains stable speeds*
  A large part of the energy consumption of a train is caused by accelerating after a stop. As long as the time schedule of a freight train matches with the available rail slots on the public transport rail network, the train can keep running. This is hardly ever the case and should be improved. Not only the amount of emissions benefits of that, it makes rail freight services more reliable as well.

Inland waterway transport

- *Optimised hull design*
  Although the design boundaries of an inland ship are not very flexible, there is quite some room for improvements in the shape of the hull. Optimising the flow to the propeller will increase its efficiency.
- *Hybrid drive systems*
  Well designed diesel electric drive systems can be more efficient than direct diesel drives. Sometimes a diesel electric configuration even takes less space on the ship, therefore increasing the capacity.
- *Shore electricity when moored at a quay instead of a diesel generator*
  A common power source for all auxiliary systems onboard is a diesel generator. This energy could also be supplied by power plugs on the quay. This way the electricity could be generated by a windmill and not by a 25 year old diesel generator.

3.3. Reducing CO_2-emissions, how can it be achieved

A lot of the developments mentioned in the previous paragraph can decrease the CO_2-emissions of a mode itself, but it always comes with a price. Especially developments in the rail and inland waterway transport sector take a long time before all trains and ships are adapted, since they are very expensive and have a long lifetime. Another way to decrease the CO_2-emissions of container transport is achieving a modal shift towards the mode that has lower emissions. The last option is to improve the efficiency of routing and fleet use, travelling fewer kilometres to deliver the same transport supply always leads to lower emissions. This seems strange because one might think that a transporting company always tries to achieve minimum costs. It is found in evaluations of road pricing schemes that trucking companies take different routes when their preferred route becomes more expensive, even when the different route was already cheaper without road pricing on their preferred route. This shows that an additional price to a certain route or mode will act as an incentive to increase efficiency and search for alternatives. This paragraph continues with the identification of different incentives to develop towards a transport system with less CO_2-emission.

One thing that the different possibilities have in common is that they all need a system to register the emissions of a certain carrier, including a structure to assign a limit or amount of rights to that carrier. Since there are a lot of companies active in the transport sector, this system might be one of the major problems that will be encountered when pricing is introduced.

Independent on the policy that is chosen to reduce the emissions of container transport, it should always work on the level of the truck, train or ship. This means that any logistical company without own equipment is not included in the policy. Handling the emissions as close to the source as possible will lead to increased costs and awareness in the whole chain. Assuming that the increased costs are always translated into a higher price for the end user of the transported product, this results in a transport system that has lower emissions.

3.3.1. Legal limitations, no CO_2-emission pricing

A simple solution to decrease the CO_2-emissions is to issue a law or regulation that limits the emissions of the sector. Each carrier receives a certain amount of rights and at the moment it has reached its maximum amount it cannot transport anymore. Companies that invest in technology that reduces their CO_2-emissions can perform more trips and therefore earn more money. This system only works when every company invests in new technology because otherwise there will be a demand for transport at the end of the year that cannot be satisfied by the supply, since there are no transporters left. This system can act as the basis for the solution in the next section.

Another possibility is to limit the emissions of the transport means. For example by forcing the carriers to reduce their emissions per transported TEU-km by a certain percentage. This will encourage the carriers to use their equipment more efficient (e.g. decrease the number of 'empty' kilometres) or to use more efficient equipment (e.g. investing in new trucks different fuel types). Downside of this type of regulation is that there is no direct control on the total amount of emissions.

It is unlikely that a system like this would work properly in practice. Differences between theoretical and actual figures on the amount of emissions will be significant, or the actual figures are not available at all. The system requires a very detailed registration system of the actual figures to work properly.

3.3.2. Pricing CO_2-emissions

Direct pricing of the emissions can be done in two ways, either all emissions are priced or only the emissions above a certain limit are priced. The first way can be achieved easily, adding an additional amount of CO_2-tax on fuel is enough. A large benefit of this solution is that no administrative system is needed to keep records of CO_2-emissions of carriers. Downside is however that there is no direct control on the amount of emissions.

This can be controlled more directly when an amount of rights is issued to all carriers, and a taxing system is constructed for the extra emissions above that amount. By reducing this amount each year, the incentive to invest in cleaner technology becomes larger by the year, so somewhere in the future the point will be reached where the carrier invests in new technology, to save the penalty he has to pay for the extra emissions. However, this results in the same problems as addressed in section 3.3.1, the registration of the emissions will be very difficult.

3.3.3. Trading CO_2-emission rights

The third system would be based on trading emission rights like it is done for large industrial facilities. Each carrier receives a certain amount of rights for a year, depending on its expected emissions. Typically, the assigned amount is too small for the carrier, so the carrier has two options. One is to invest in more efficient technology; the other is buying rights from carriers that have sufficient rights. The rights are traded on a market and the price will be a result of demand and supply. A downside of this system is that each carrier has to trade their own rights, which might be difficult to understand, and it is likely that a lot of carriers do not want to do that. Agents will appear that can do the trading for the carriers, but that costs money as well, money that cannot be spend on decreasing the CO_2-emissions.

3.4. CO_2-emission pricing scenarios

In the previous paragraph, a couple of possible instruments are introduced. Of the instruments, pricing seems the one with the best result, because it is a system that requires the least administrative systems and is felt directly by the carriers. It is chosen to add an additional tax on energy, the easiest possibility. As an addition to pricing, other policy measures and changes in the network will be addressed too. The scenarios that will be used are addressed in the next sections. An important assumption in all scenarios is that the container flow between the origins and destinations will remain the same as in the reference scenario. In practice this is not necessarily right, it is in fact more likely that the total transport volume goes down when the transport costs increase. When transport becomes more expensive, the locations of production facilities, warehouses and distribution centres could change, causing a change in the flow of containers between the chosen origins and destinations. This is a strategic choice of individual companies and that is not the focus of the research.

3.4.1. Reference scenario

This scenario has no CO_2-emission pricing. It is used to validate and calibrate the model as close to the real situation in 2006 as possible. The results of this scenario are addressed in paragraph 4.3.

3.4.2. Scenario group A - CO_2-emission pricing

Adding a certain price for CO_2-emissions has different results for different modes and might therefore lead to different mode and route choices. The price of CO_2 is varied between €10 and €200 per ton, this means, for example, a fuel tax between €0.05 and €1.09 per litre diesel for road transport. The increase of the fuel price seems to be very high, but one has to consider that the current price of CO_2 in the European Trading Scheme is around €15 per ton (J Cozijnsen, 2010).

Expected results

Since the emission of CO_2 is directly related to the energy consumption of the carrier, it is expected that the carriers that use less energy per TEU-km will benefit from CO_2-emission pricing. This results in a modal shift towards rail and inland waterway transport. It is also expected that the modal shift and network use changes in steps, because an increase in the CO_2 price leads to a decrease of the critical distance to make intermodal transport cheaper. At the point that this distance becomes smaller than the distance between two centroids, a new origin-destination pair will benefit from intermodal transport as well and the modal split changes.

3.4.3. Scenario group B - Additional policy and developments

To increase the effects of CO_2-emission pricing, some additional scenarios will be investigated as well. For example a subsidy on biodiesel for trucks would result in cheaper road transport that might lead to a different modal split. On the other side, using regulation to force trucks to use a certain percentage of biodiesel may lead to more expensive road transport that has lower CO_2-emissions.

Regulate the use of bio-fuels in road transport

Running a diesel engine on something else than pure diesel is not a new idea. When Rudolph Diesel invented the diesel engine, he used peanut oil to run it. There are a lot of sources available to create mixtures of biodiesel, even pure biodiesel (B100) is available to the market. Mixtures like B05 or B30, are mixtures of diesel and 5 or 30 percent biodiesel. Currently, the diesel that is sold in gas stations is B05, so only higher mixtures are improvements. Quite some initiatives to make the use of biodiesel more common are available, one of them is a project of the province of Gelderland, FUELswitch. This project focuses on sharing information about the available technologies and the benefits of using cleaner energy sources in transport (FUELswitch, 2010). It states that using B100 would result in 68% less CO_2-emissions, but the fuel costs will be approximately 25% higher. The reduction of CO_2 is a result of the source of the biodiesel: rapeseed, a quickly growing plant that absorbs CO_2 from the air while it is growing.

A quick review of gas stations that sell biodiesel resulted in prices of B100 and B30 that are 50% and 25% higher than normal (B05) diesel. Besides the higher costs per litre, a truck needs some adaptations to be able to run on B100, which cost around €3000 per truck. This shows that changing from normal diesel to B100 is not a wise decision from a business perspective, so subsidies or legislation needs to force the change.
The scenarios that will be used with a range of pricing scenarios are:

- B1: Road transport is forced to use B30, so 20% less CO_2 at a fuel cost increase of 25%
- B2: Road transport is forced to use B100, so 68% less CO_2 at a fuel cost increase of 50%

It is expected that the regulations cause a modal shift from the road to rail and inland waterway transport, until the CO_2 price reaches the level where the difference in fuel costs is compensated.
One more possibility is to force inland shipping to use biodiesel as well. This will lead to a modal shift back to the road, because inland shipping becomes more expensive. Independent of the modal shift, the total emissions can still be lower.

- B3: Inland waterway and road transport is forced to use B100

A large increase in the price of oil

It is not unlikely that a large increase in the price of crude oil will take place in the future. The fuel costs of all modes will more or less follow that increase and a modal shift will be the result, since road transport will be affected more than inland shipping. CO_2 pricing is not investigated in this scenario, it is assumed that the effects are similar to scenario group A.

- B4: The fuel costs of all modes will increase by 100%

3.4.4. Scenario group C – Changes in the network

If the use of the network changes to a large extend, it might be useful to add or remove terminals or other infrastructure. This is not seen as a goal of the research, but it is interesting to look what the number of transhipments would be at the added terminals. The locations of the imaginary terminals are based on plans for the future or locations that were planned but not developed into a terminal.

Adding a barge terminal in the region of Dordrecht

A potential solution to the congestion on the A15 is to have a large container terminal in the area of Dordrecht/Alblasserdam (M van Schuylenburg *et al.*, 2008). An optimized barge shuttle service to the terminals on the Maasvlakte and in the future Maasvlakte II could provide a first leg of hinterland transport and the terminal could act as a depot for empty containers. Building such a terminal leaves two options, one to use it as an additional access the port of Rotterdam where only truck to ship and vice versa transhipments are done, and one that could tranship containers from ship to ship as well. The first option requires a terminal that has limited quay length and storage space, the second option needs a larger terminal. The transport costs of the ships that operate between the Maasvlakte and the new terminal are not necessarily the same as the ship that operate on the longer distances. The costs could be higher due to the lower number of sailing hours that are a result of the amount of time that is spend at the terminals while loading and unloading. On the other hand, the costs could be lower because the ships can be loaded to maximum capacity most of the times. It remains questionable whether a terminal in the area can attract sufficient flows, since all transport chains that use the terminal, use one more transhipment than chains that do not use the terminal. This extra transhipment results in, by definition, higher costs of the total chain.

- C1 Adding a barge shuttle service between the Maasvlakte and Alblasserdam

Adding a rail terminal in Valburg

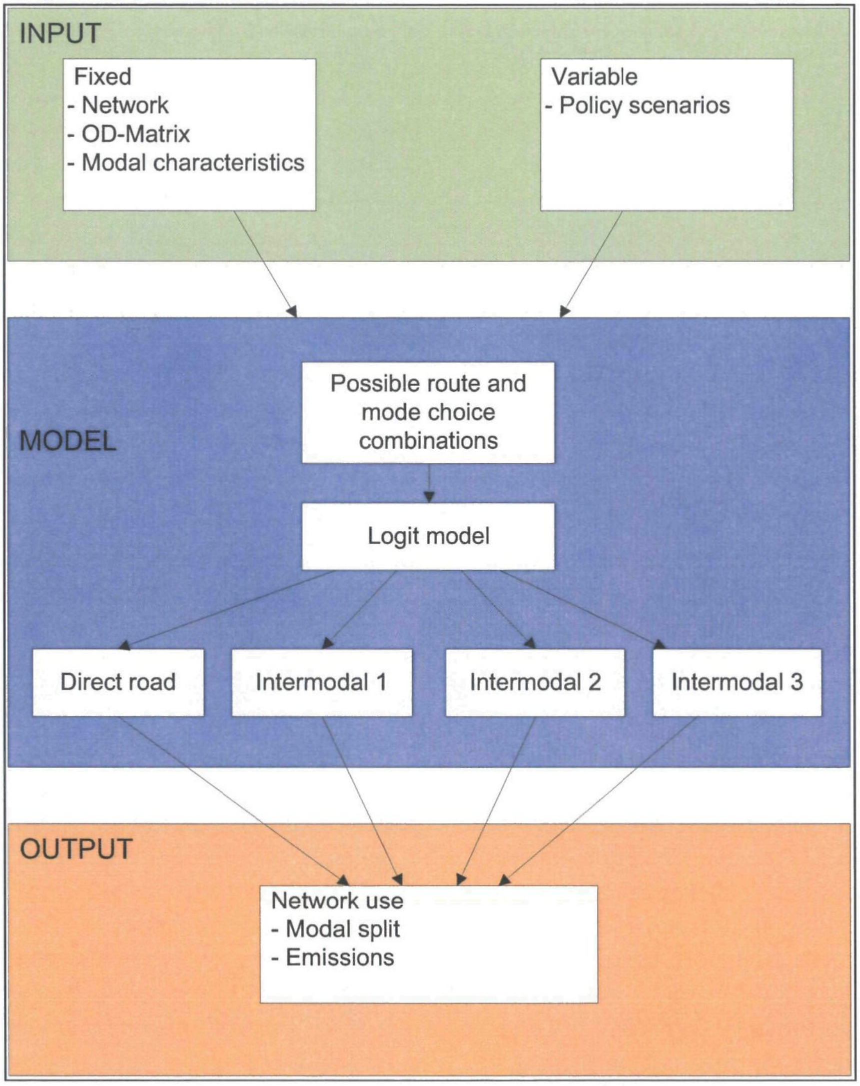
In the second half of the 90's, a lot of effort and money was invested in the planning of a multimodal transport centre in Valburg. The area is connected to the highway A15, the Waal and the Betuwelijn, which was not yet constructed at that time. Eventually the plan did not succeed because of lots of different reasons. Instead of the large intermodal centre, only a barge container terminal is constructed in Nijmegen, just a few kilometres up the river. To look at the effect of a rail terminal in the area, a terminal is added in this scenario.

- C2 Adding a rail terminal in the area around Valburg

4. Modelling container transport

In general, the model consists of three parts. In the first part, the input for the model is determined. The actual transport model then calculates the possible routes, chooses the least expensive one and assigns the freight flow to the network. The last part creates the output, maps of network use and general indicators like modal split and total transport costs in the system. The parts of the model are visualised in figure 4.1.

Figure 4.1: Overview of the model



The input box of figure 4.1 divides the input in two parts, a fixed part and a variable part. The fixed part is constant in scenario group A and B, the variable part are the different policies. The fixed part consists of:

- the O-D matrix with the general container flows between regions, independent of the modes that are used
- the physical infrastructure network of roads, rails, inland waterways and terminals
- the characteristics of the modes

The model is built in OmniTRANS 5.1, using the public transport module. The network of roads, rail- and inland waterways act as a super network, which is used by transit lines of the specific modes. The program is able to assign the transport flows to the route with the lowest generalised costs. The assignment of the transport flows will be discussed in paragraph 4.2.2, the calibration and validation of the model in paragraph 4.3. The next paragraph will elaborate on the input of the model.

4.1. The input of the model

The transport model will assign the freight to the network based on the routes with the lowest transport costs. Therefore, the most important inputs are the cost functions of the modes, sections 4.1.2 and 4.1.3 will elaborate on this. The two other fixed inputs, the networks and the OD-matrix, are already defined in paragraph 2.4.3 and 2.4.4. The variable input is already defined in paragraph 3.4. This paragraph starts with an overview of assumptions that have influence on the model in general.

4.1.1. General assumptions and limitations of the model

Creating a model always involves assumptions about decision making processes in the real world. Some of the processes can be modelled accurately, others need to be averaged or cannot be modelled at all. The following list shows an overview of the general assumptions that are made before the model is created.

- *The shipper makes route and mode choices, for every single container*

  When a shipper needs to ship a lot of containers during a year, he often uses long term contracts with a transporter of forwarder. This contract is unlikely to be changed every time something changes in the transport costs, so the route and especially mode choice will be more or less fixed for the entire contract. It is likely that the route choice could be changed by the transporter to optimise the use of their carriers. This is not taken into account in the model, every container between a certain origin and destination is handled with the same cost functions. This assumption also means that is possible to change the decision, based on the costs only. In reality, there are many causes that make such a change impossible.
- *The route and mode choice is based on costs*

  It is hardly ever possible to get insight in the margins that all actors use on top of their costs to calculate a price for the transport. The margins in road transport are small because it is a highly competitive market; for inland waterway transport the margin is around 10% (Rabobank, 2010) and for the rail sector and the terminals it is unknown. This makes it very hard to make a decision that is based on the price the shipper actually pays for the transport it needs. It is assumed that the margins are all within the same range and using costs as a comparison is sufficient.
- *Once the route and mode choice is made, it is possible to use it*

  In practice it is possible that the route of choice is not available, due to many causes. An example is the availability of slots for freight trains. This is very hard to model and therefore it is assumed that the route of choice is always available.
- *An increase in transport costs does not lead to less transport demand*

  Whenever transport becomes more expensive, a number of shippers will decide not to transport their product from location A to location B. It is possible that they decide to transport it to location C, or not to transport it at all. This will result in a different OD-matrix, and therefore different network loads. It is assumed that this effect is too small to include redistribution of the freight flows in the model. It is also found in literature that the price elasticity of the total amount of freight transport is lower than -0.1 (G P Geilenkirchen *et al.*, 2010).
- *The origins and destinations are the production and consumption locations*

  The container flows in the OD-matrix that is used, gives flows between two regions. However, it is possible that these are not the actual origin and destination of the container. For example, a container that is transported from region A to region C, but is transhipped in region B, can appear in the matrix twice (from A to B and from B to C). Therefore, a new route that goes from A to C directly, will never be assessed by the model.
- *No difference between empty and loaded containers*

  Empty and loaded containers do not have the same characteristics and therefore, the transport choices will be different as well. Even within the group of empty containers differences appear. The hinterland transport could be identified as carrier haulage when it is arranged by the ocean shipping line or as merchant haulage when the hinterland transport is arranged by another actor. In case of carrier haulage, the return trip with the empty container is included in the price the shipper pays and it is likely that it is transported in a similar way than when it was still loaded. In case of merchant haulage, the receiver is responsible to return the container at the location where the owner of the container wants to have it. This is subject to the strategy of the owner and it is hard to make a distinction between all those possibilities. Therefore it is chosen that the empty containers are handled the same way as the loaded ones.

- *No empty trucks/trains/ships on the return leg*
  If a truck delivers a container at its destination, the truck will possibly leave to pick up the next load. During this repositioning process, the truck is empty. This is also possible in rail and inland waterway transport. The empty carriers are not included in the model because repositioning empty carriers is a strategic choice of the owner of the carrier, while the modal is on a system level.
- *Occupancy rates of carriers do not change*
  When one of the modes transports more containers in a new situation, there are two possibilities. The first one is that there is no capacity in the current fleet, so a new carrier is needed. The other one is that the capacity of the fleet is sufficient, so the increased volume can be transported. In the first situation, the occupancy rate does not change, in the second situation it becomes higher. This leads to lower costs and emissions, which could lead to a further increase in volume. In a model, this could be done by multiple iterations in one run, but the effects of it are assumed to be small enough to be neglected.

4.1.2. General transport cost function

This section elaborates on different types of cost functions that are found in literature and concludes with the structure of the cost functions that will be used in the model. In the transport market, the costs are on the supply side, since it is a characteristic of the transport services that are available to supply the shippers' demand. However, the shippers always have to pay a price, so costs plus a profit margin for the transporter. It is difficult to estimate the profit margins in the transport sector, since it varies a lot over the type of transport, but in general it can be assumed that the profit margin is very low. Therefore it is valid to use transport costs as a comparison instead of transport price.

Total logistical costs

Looking at transport from a business logistics perspective, the costs of transporting a good from a supplier to a receiver have a broad definition. Besides the actual costs of transportation, stock cycle costs and safety stock costs need to be included (G Blauwens *et al.*, 2006). In the article, the following cost function is used:

$$TLC = TC + \left(\frac{1}{R} * \frac{Q}{2} * v * h\right) + \left(L * v * \frac{h}{365}\right) + \left(\frac{1}{R} * v * h * K * \sqrt{(L * d) + (D^2 * l)}\right)$$

The first term, TC, are the transportation costs of the shipper. The second term are the costs of the cycle stock, depending on the annual volume, R; the shipment size, Q; the value of the foods, v; and the holding costs, h. The third term represent the inventory costs of the goods during the transport, L is the lead time of the transport. The last term represents the costs of keeping a safety stock and depends on a safety factor, K; and the average values and variances of the daily demand and the lead time. Looking at the transport market, the first term represents the supply side, the other three are costs of the shippers and therefore they belong to the demand side of the market.

In the article, the cost function is used to evaluate the effect of different policy options in a hypothetical container transport market. Applying it on the actual container transport market is very difficult, since the costs are calculated for specific supplier-receiver relations and too many variables in the function are unknown. This leads to the conclusion that the cost function in the model should focus more on the transport costs than on the logistical costs.

NODUS

In the Belgian transport model called NODUS, described by (B Jourquin *et al.*, 1996), the following cost function is used:

$$TC = \sum_{i \in l_i} \sum_{j \in l_j} \sum_{\theta} \left[\left(B^{\theta} + \frac{a^{\rho}}{v^{\theta}} \right) * s_j + \left(a^{\theta} + a^{\lambda} + a^{\rho} \right) * H_i^{\theta} \right] * Q_{l\theta}$$

$Q_{l\theta}$ is the flow on route l, that consists of "handling" links i, and "moving" links j. θ is the index for the mode that is used on a link. The handling links are the places in a route where the freight is transhipped, loaded or unloaded. The moving links are the parts of the route where the freight is actually moving from origin to destination. This division is also recognised in the cost function. The first part $\left(B^{\theta} + a^{\rho}/v^{\theta}\right) * s_j$, describes the costs related to the distance s_j. The first term are the transport costs of the carrier, the second term are the opportunity costs a^{ρ} of value of the freight while it is transported with an average speed of the mode v^{θ}. The second part of the cost function give three time related factors for the handling links, a^{θ} for the time related costs of the handling, a^{λ} for labour costs and a^{ρ} for the opportunity costs, with H_i^{θ} being the time that is used for handling operations. Again, it can be recognised that there is a part in the function that belongs to the supply side (B^{θ} and a^{θ}) of the transport market, and a part that belongs to the demand side (all the other terms). Something that should be noted about this function is that it does not make a division in average speed on "moving" links. It only takes the average speed of a mode into account and therefore it is not possible to differentiate between congested and uncongested links. Another aspect that should be noted is that the external costs are not taken into account either.

Cost function in this model

Rewriting the cost function to take the two notes into account leads to the following formula for the generalised transport costs of one TEU from origin i to destination j (note that i and j have a different meaning than in the previous function):

$$GC_{i,j} = CDC_{i,j} + CTC_{i,j} + TC + EC_{i,j}$$

In the formula, four different parts can be identified: $CDC_{i,j}$ or Carrier Distance Costs, the costs that depend on the distance between i and j; $CTC_{i,j}$ or Carrier Time Costs, the costs that depend on the time it takes to transport the container from i to j; TC are the transhipment costs and $EC_{i,j}$, the emission costs that are made between i and j. The first four parts will now be discussed.

$$CDC_{i,j} = \textstyle\sum_m C_{dm} * d_m$$

$$CTC_{i,j} = \sum_m (C_{tm} + VoT_m) * \frac{d_m}{v_{m,link}}$$

$$TC = \sum_t C_{T,t}$$

$$EC_{i,j} = \sum_m EC_m * d_m$$

Table 4.1: List of abbreviations of the formulas

	description	unit
m	Index for the mode	-
d_m	Distance per mode	km
C_{dm}	Distance costs of the mode	€/TEU-km
C_{tm}	Time costs of the mode	€/TEU-h
VoT_m	Value of Time, mode dependent	€/TEU-h
$C_{T,t}$	Costs of transhipment at terminal t	€/TEU
t	Index for the terminal that is used	-
$V_{m,link}$	Average speed of a mode on a link	km/h
EC_m	External costs of modalit	€/TEU-km

The distance related costs per TEU are straight forward, depending on the modes used on a route; it is the sum of the costs per kilometre multiplied with the distance of each mode. The transhipment costs are simple as well; it is just the sum of the transhipment costs at the terminals that are used. The time dependent of the costs are defined as all costs of a carrier that are not depending on distance. Being able to separate time and distance related costs leads to the situation where the transport costs depend on the speed on a certain link. A link that is commonly congested can then be given a lower average speed, which leads to higher costs on that link, exactly the effect of congestion. In this cost function, the demand side of the market is represented by the value of time supply side by the other terms.

4.1.3. Cost functions of all modes

This section elaborates on the cost functions of all modes. Table 4.2 recalls the division of means of the modes.

Table 4.2: The division of the modes into means

Mode:	Road	Rail	Inland waterway
Means	Euro V	Diesel	Class II
	Euro VI	Electrical	Class III
	LHV		Class IV
			Class Va
			Class VIb

For road and rail transport, the cost functions are derived from "Factorkosten in het goederenvervoer" (NEA, 2004). To have a clear picture of the structure of the costs in that report, the structure needs to be discussed. In (NEA, 2004), the costs are divided into five components:

Fixed costs	depreciation, interest, road tax and insurance
Variable costs	maintenance, repairs, fuel
Labour costs	wages
Specific transport costs	special equipment, licenses, permits
General business costs	Offices, other personnel, ICT

This division of the costs needs a critical note, since costs are by definition either fixed or variable. Somehow, NEA created three additional categories that are all part of the fixed costs. The report creates transport costs that depend on either distance, time or a combination of both, so the five components have to be divided a bit more. First of all, the fixed, specific transport and general business costs are considered to be indirect costs, since they are not depending on the use of the carrier. The variable costs are defined as distance dependent direct costs and the labour costs are time depending direct costs. The assumption that fuel is only depending on the distance is only true when an average fuel consumption is used that is based on a very large number of samples. The indirect costs are divided over the operational hours in a year and added to the time depending direct costs. This results in transport costs that depend on both time and distance. The figures are corrected by the product of the occupancy rate and the load factor.

Road

The first two road transport means have almost the same cost functions. The only difference between a Euro V and Euro VI truck is a small increase in fuel consumption. It is assumed that this increase is 1% and that it only influences the CDC of the truck. In (NEA, 2004) it is found that a large truck, carrying two TEU's has a CDC of €0,40 per kilometre and CTC of €56,4 per hour, at a price level of 2002. These prices should be corrected to the level of 2006; the CDC mainly consist of fuel costs and should be corrected by the change in fuel price, the CTC are costs like wages of the driver and investment costs and will be corrected by inflation. The average fuel price in 2002 was €0,788 €/L, which increased to €1,087/L in 2006, an increase of 37,9%. The inflation in the same period was around 10% (CBS, 2010). For the Large Heavy Vehicles (LHV), information is found in an evaluation of the trial in the Netherlands (Arcadis, 2006). It is stated that the average fuel consumption of a LHV that carries three TEU's is 25% higher than a normal truck. It also states that the other costs are 25% higher as well. This clearly shows that the LHV has benefits of scale; the costs of a single LHV are 25% higher than the costs of a normal truck, while the capacity is 50% higher. Per TEU this results in transport costs that are 17% lower. All the costs are calculated and shown in table 4.3.

Table 4.3: Costs of the three road transport means

Means	CDC (€/TEU-km)	CTC (€/TEU-h)
Euro V	0,2759	30,98
Euro VI	0,2786	30,98
LHV	0,2300	25,81

The road transport that is used for pre and end haulage has different costs than direct road transport. Waiting and loading time at the origin, terminal or destination have a lot of influence on the costs. Besides that, pre and end haulage involves a lot of accelerating of the truck, which causes extra fuel consumption. This causes a total cost increase for pre and end haulage of 89% (M Savy, 2001).

Rail

In (NEA, 2004) rail transport is only available as one mode, no division is made between a diesel or electrical driven train. Another report, 'Vergelijkingskader Modaliteiten' (NEA, 2001), does make a distinction between the two, although the data is a bit older since it is of 1999. Just as for road transport, information of the CBS is used to correct the prices of fuel, electricity and other costs. The costs are summarised in table 4.4.

Table 4.4: Costs of the two rail transport means

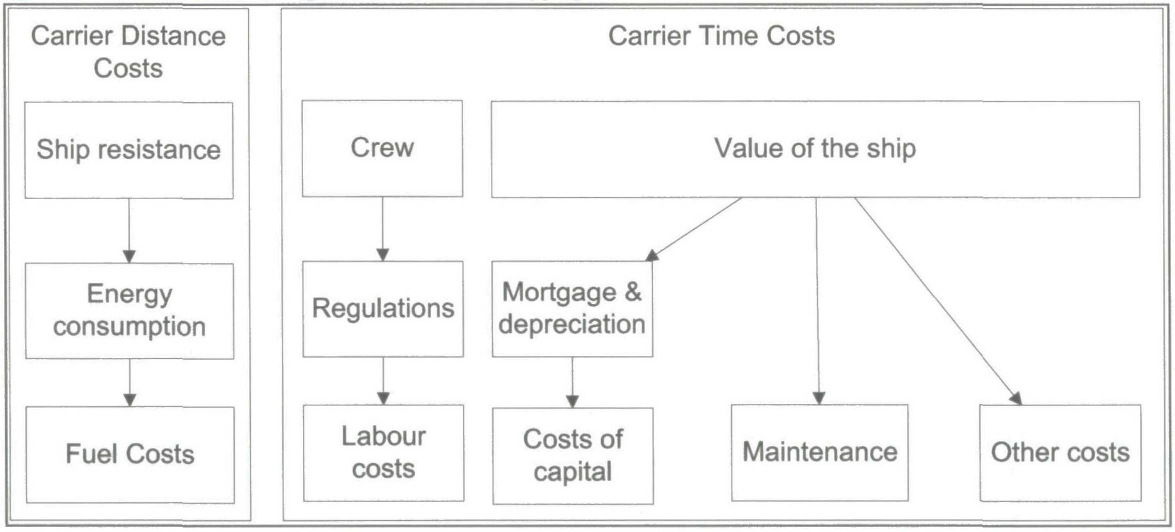
Means	CDC (€/TEU-km)	CTC (€/TEU-h)
Diesel	0,02482	7,194
Electrical	0,06437	7,540

Inland waterway

For the costs of inland waterway transport a different approach is taken. There is a large difference in costs between a class VIb ship on the IJsselmeer and a class II ship on a narrow and shallow canal. Since the resistance of a ship is less than proportional to the size, there are significant benefits of scale, as long as the occupation rate is sufficient. The method that is used to calculate the costs of each mode is shown in figure 4.2, the results are described on the next page. It is clear that the distance related costs only depend on the fuel consumption, while the costs of the crew, capital, maintenance and several other components are only depending on time.

The costs are calculated with fuel prices and labour costs of 2006, at the end of the section a comparison will be made with figures of the Rabobank and NEA to validate the costs.

Figure 4.2: Method of calculating the costs of inland shipping



The fuel costs can be derived from the energy consumption that was calculated in paragraph 3.1.3. These fuel consumptions are multiplied by a fuel price of €500/ton, this results in fuelcosts per TEU-km, which are shown in table 4.5.

Table 4.5: Fuel costs in €cents/TEU-km, a, b and c are: deep water, 2*draft and 1,5*draft

	Class II			Class III			Class IV			Class Va			Class VIb		
Km/h	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
6	0,56	0,56	0,59	0,48	0,48	0,51	0,24	0,24	0,25	0,25	0,23	0,25	0,37	0,37	0,40
8	0,96	1,01	1,10	0,82	0,87	0,95	0,41	0,43	0,47	0,41	0,41	0,46	0,59	0,64	0,73
10	1,48	2,02	2,24	1,41	1,67	1,87	0,69	0,82	0,93	0,68	0,77	0,88	0,92	1,17	1,38
12	2,21	2,84	3,25	1,87	2,48	2,85	0,91	1,23	1,42	0,91	1,18	1,39	1,20	1,78	2,17
14	3,33	4,88	5,84	2,79	4,19	5,05	1,34	2,06	2,50	1,32	1,98	2,45	1,64	2,88	3,75
16	5,11	9,76	13,4	4,22	8,05	10,7	2,01	3,94	5,29	1,94	3,75	5,12	2,29	5,32	7,66
18	7,93	21,1	42,4	6,42	16,3	31,7	3,06	8,02	16,0	2,90	7,42	15,6	3,27	10,3	26,6

The labour costs depend on the requirements on the crew that needs to be on the ship, these are found in (NEA, 2003). Some ships are operated by two complete crews that work every other two weeks, in that case the labour costs are twice as high. In practice this is only the case for ships that are operated by larger companies, which is only a limited amount of the fleet. For the smaller ships this is hardly ever the case so one crew is sufficient. To take this into account, the labour costs of the four largest ships are multiplied by a factor 1,25. This means that only one out of four ships is operated by two crews, the other three are operated by a single owner and crew. Another important assumption is that the captain of the ship is paid from the profit of the company and not by a regular salary. The salaries of the crew are found in the Collective Workers' Agreement (Kantoor Binnenvaart, 2005).

The value of the ship also takes a large part of the costs, the costs of capital. A common structure of financing an inland ship is 70% mortgage and 30% equity. The mortgage has a payback period of twenty years at an interest rate of 5% (Rabobank, 2010). The owner of the ship also needs some interest on his investment, the equity part, but it is assumed that the interest on equity is paid from the profit that is made. The profit is not a part of the cost function, so the interest on the equity is irrelevant. The value of the ship is difficult and very volatile since it depends on the market. As a rule of thumb, the price of a ship can be estimated by €2600 per ton steel and €250 per installed kW . Besides the mortgage, also depreciation is taken into account. It is assumed that owners depreciate their ship to a book value of zero in 25 years. Using the new build prices of ships has one difficulty: the fleet does not entirely exist of new ships. A database of an inland shipping community (Vereniging de Binnenvaart, 2010) is used to estimate the average age of inland ships in the Netherlands. Class II and III are generally older than 30 years, but some value needs to be assigned to the engines that are replaced every 10 years. Class IV is about 10 years younger, the average age of a Class Va ship is 10 years and the largest ships, Class VIb, are a development of the last 10 years and average an age of 5 years. The remaining cost components, maintenance and other costs, are assumed to be 1,5% of the new build price of the ship.

Table 4.6: Cost characteristics of the different ships

	Class II	Class III	Class IV	Class Va	Class VIb
Sailing hours [h]	3066	3066	3592	4117	4117
Loading degree [-]	60%	70%	60%	80%	90%
Labour costs [€/year]	26.212	49.350	51.950	86.750	86.750
New build price [€]	866.600	1.499.000	1.860.650	3.191.350	6.164.700
Value in % of new build price [-]	20%	15%	100%	100%	100%
Costs of Capital [€/year]	18.050	23.200	108.900	300.800	613.400
Maintenance costs [€/year]	8.650	15.000	18.600	31.900	61.650
Other costs [€/year]	4.350	7.500	9.300	15.950	30.800

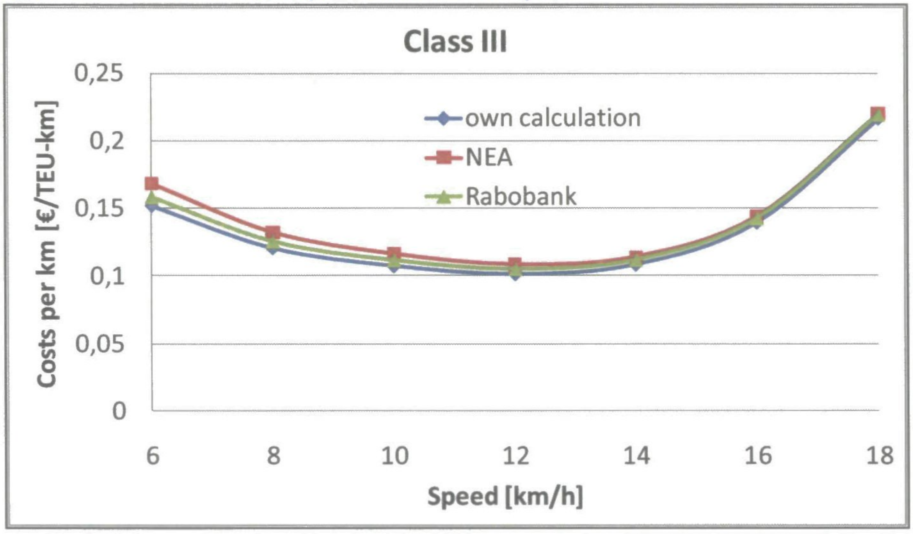
The last thing to calculate the cost functions is correcting all the figures with the loading degree. The idea is that all time related costs are paid in the time that the ship is sailing and divided over the containers that are on board. The distance related costs are only divided over the containers on board. The sailing hours of the ships are derived from (NEA, 2003), the loading degrees are estimated by comparing the costs to figures from NEA and the Rabobank.

Table 4.7: Costs of the inland waterway means, CDC in €/TEU-km and CTC in €/TEU-h for 2*draft

	Class II		Class III		Class IV		Class Va		Class VIb	
Speed	CDC	CTC	CDC	CTC	CDC	CTC	CDC	CTC	CDC	CTC
6	0,0342	1,100	0,0147	0,8493	0,0080	0,6938	0,0048	0,6122	0,0059	0,5165
8	0,0417	1,100	0,0203	0,8493	0,0112	0,6938	0,0057	0,6122	0,0089	0,5165
10	0,0585	1,100	0,0317	0,8493	0,0177	0,6938	0,0093	0,6122	0,0147	0,5165
12	0,0722	1,100	0,0433	0,8493	0,0243	0,6938	0,0134	0,6122	0,0216	0,5165
14	0,1062	1,100	0,0677	0,8493	0,0383	0,6938	0,0213	0,6122	0,0337	0,5165
16	0,1875	1,100	0,1229	0,8493	0,0697	0,6938	0,0391	0,6122	0,0609	0,5165
18	0,3762	1,100	0,2411	0,8493	0,1377	0,6938	0,0757	0,6122	0,1161	0,5165

Validating the calculated costs is done by comparing it to figures of NEA and the Rabobank. The Rabobank provided an averaged and normalised cash flow statement of dry cargo inland shipping companies in 2008, available in Appendix VIII. NEA also presented an overview of the cost components in (NEA, 2003). Since both sources give percentages, it is possible to start with the calculated fuel costs and then calculate the total costs. This is no longer done in a time and distance dependent part, but only as distance related costs as a function of the speed. As an example, figure 4.3 shows the three different sources, the graphs of the other ship types are found in Appendix IX.

Figure 4.3: Costs of a Class III ship as a function of the speed



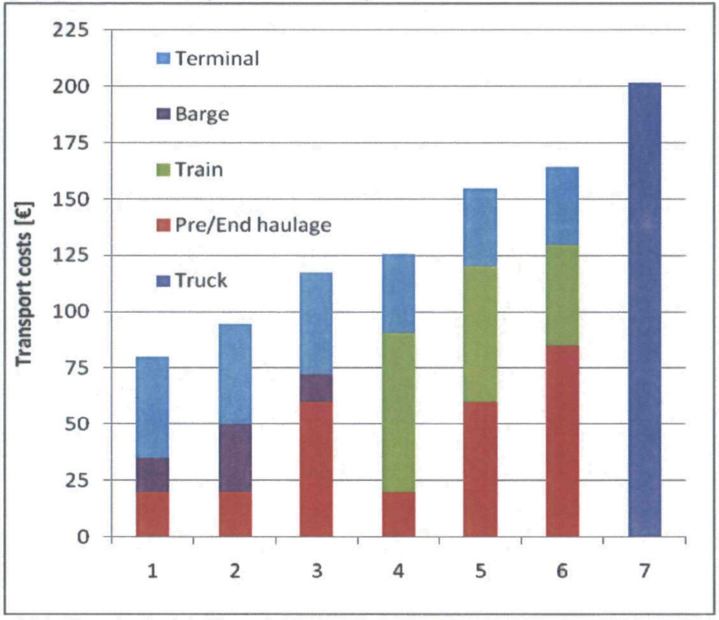
All three lines follow the same trends and are very close in values, it is therefore concluded that the method that was used to calculate the costs of inland ships is valid and that the results can be used in the model.

Another conclusion is that the total costs are really depending on the speed, going faster saves time dependent costs, but that trade-off is only true up to 12 km/h for a class III ship. Above that speed, the costs are rising again. This leads to the conclusion that the costs need to be dependent on the speed in the model as well.

Comparing the costs, an example of a route from Rotterdam to Heerlen

To show the differences between the possible uni- and intermodal routes, the following comparison is made: the transport costs of a container from the ECT Delta Terminal in Rotterdam to the city Heerlen are calculated for seven different routes.

Figure 4.4: Modal composition of transport costs on seven routes between Rotterdam and Heerlen



Route	Mode	Terminal used
1	Va Ship	Born
2	II Ship	Born
3	Va Ship	Venlo
4	Train	Born
5	Train	Venlo
6	Train	Eindhoven
7	Truck	None

Conclusions about the costs of the transport means

The costs of the transport means consist of three parts: distance related costs (CDC), time related transport costs (CTC) and the costs of the CO_2-emissions. The CDC and CDC of road transport are presented in table 4.3, of rail transport in table 4.4 and of inland waterway transport in table 4.7. The two remaining parts of the costs function in the model are the transhipment costs and the value of time of the freight, which is explained in the next section.

4.1.4. Dealing with other decision parameters

As described in paragraph 2.3, the choice of using a certain mode is not only depending on the costs of the transport. The demand side of the market also has requirements on the transport services that are chosen. It is, however, more difficult to monetize these requirements. Value of time is often used as a representation of the factors that are not cost related and influence the choices of shippers. On micro level, for example, the mode choice of a specific company that needs to transport a specific type of freight, can be done accurately. On a macro level, this is completely different because one needs more characteristics about the freight that is inside the containers than are available.

An important note that needs to be made is that value of time is considered to be a more logistics related choice parameter than a transport related one, because it is clearly on the demand side of the market. On the macro level, average values are used for large groups of containers, but it is unlikely that the average containers exist. This is the reasons that there are different ways to model the effects of the value of time. Part of the mode choice could be done with a stochastic parameter (M Ben Akiva *et al.*, 2008; T G Crainic *et al.*, 1996) that depends on not only the value of the freight, but can be dependent on quality, reliability or demanded shipment size. It can also relate to the urgency of a shipment, if a container needs to be transported from Groningen to Rotterdam within a few hours, it is not possible to do that with intermodal transport.

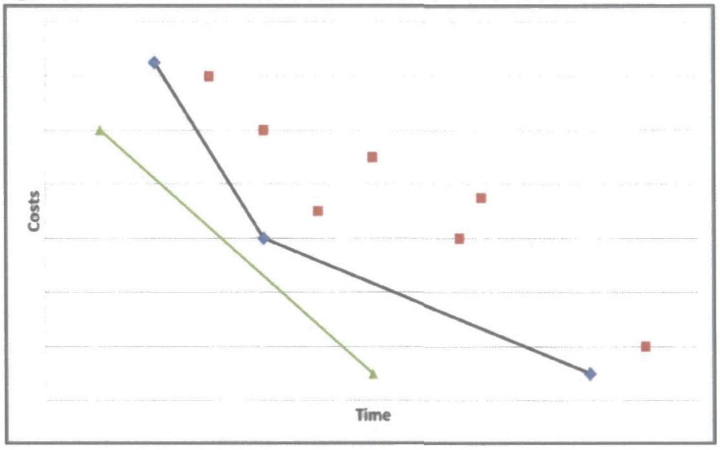
Another important note is that it is not necessarily valid to add the costs of the shipper to the costs of the transport. This can only be done under the assumption that the shippers really make their choices based on the sum of the costs and for every single shipment. As described in the previous section, this assumption is made. There are however situation where this is not valid:

- An increase of the transport costs of a company can always be smaller than investments that are needed to redesign the supply chain of the company. In this case, the shipper accepts the increased transport costs, but does not change its choices.
- When a shipper contracts a carrier to arrange its transport in periods for a year, it is unlikely that changes in the transport costs during the contracted period lead to different choices. Especially when the contracted carrier can only provide transport by one mode.
- There will always be companies that have a transport department that wants to minimize their costs and a production department that tries to minimize the costs as well. When the communication between the departments is not sufficient on a strategic level, choices that minimize the total costs but increase the costs of one of the departments, are unlikely to be made. In this case the two parts of the shippers' transport costs are never summed and it would not be valid to do so while modelling the transport of these companies.

Theory behind value of time

Each origin and destination is connected by multiple routes, unimodal and intermodal. Each route has specific transport costs and transport time, usually the faster routes are more expensive than the slower ones. The trade off between a faster, but more expensive route, and a slower, but less expensive route, will be judged by the shipper and depends on specific variables in his logistic and production demand. All possible routes can be projected as points in a chart, see figure 4.5.

Figure 4.5: The relation between time and costs of different routes



The costs in this figure, are the total costs of the transport, so including the costs that shippers are not paying to the transporter.

The three blue points are very important, in this example the left one is direct road transport, the middle on is intermodal transport with a rail leg the right one is intermodal transport with an inland waterway leg. The red points are sub-optimal solutions, since there is always a faster and less expensive alternative available.

The green line shows an example of the valuation of travel time of a certain product and shipper, the slope of the line is the value of time. The black line between the blue points represents the value of time of the possible transport solutions. The optimal solution for a container with a given value of time, is the solution where the green line intersects with one of the blue points, with the smallest perpendicular distance to the origin of the graph (R.B. Dial, 1979). In this case, this is the point in the middle. However, to do this, information about the distribution of the value of time over the total number of containers in the market is required, which is not available.

Values of time in this research

The lack of information about the distribution of value of time is solved by using survey data that describes the average value of time of containers that are transported by road, rail or inland waterway (G. de Jong *et al.*, 2003). The values are already presented in Paragraph 2.3.

The value of time figures in table 2.9 consist of two parts, one that is related to the transport and one that is related to the freight inside the container. The first part is already present in the cost functions in the previous section, e.g. the Carrier Time Costs, and needs to be subtracted. The result is the part of value of time that is related to the freight. This results in a value of time that is dependent on the mode that is used. This works for road and rail transport, however inland waterway transport has a negative value. In theory this is possible, for example when the freight gains market value while it is on board, but in general it is unlikely that this is true. The value that is chosen for inland shipping is €0,05/TEU-h.

To prevent a change of value of time when a container is transhipped, the difference in value between the modes is compensated in the same way as the cost difference of pre and end haulage, explained in the previous section. The chosen values of time are shown in table 4.8.

Table 4.8: Value of time calculation in €/TEU-h

	Road	Rail	Inland waterway
Total value of time (G. de Jong *et al.*, 2004)	42	11,56	0,542
Carrier Time costs (NEA, 2004)	30,98	7,54	0,7
Value of time	11,02	4,02	0,05

Logit function

Even when value of time is included in the cost function that is used to make a route and mode choice, there are containers that are not necessarily transported by the cheapest alternative. A couple of situations where this can happen are discussed earlier. To model these effects as well, the logit model is often used (D McFadden, 1974). This is a model that calculates probabilities of using alternatives that have a given difference in costs. The logit function is implemented in the OmniTRANS software, the way how it is used will be discussed in section 4.2.2.

Conclusions about other decision parameters

Data about the value of time of the freight that is inside containers is not available on a container level. There is however data about the average value of time of containers that are transported by road, rail or inland waterway transport. These values are presented in table 4.8. To take effects of choices that are not based on any kind of costs into account as well, a logit function is used to spread the containers over different available routes.

4.2. From input to output, how the model works

This paragraph will elaborate on the way the model works, the simplifications that were necessary and the algorithm that is used by OmniTRANS to solve the assignment. A lot of the decisions are based on the capabilities and limitations of the software, which resulted in an alternative approach than found in literature. The NODUS model, mentioned in the previous paragraph, uses a virtual network of mode dependent links, on top of a super network of the infrastructure links. Terminals are modelled by a small handling link. If a certain infrastructure link can be used by three types of vehicles, the virtual network consists of three links, each with the mode dependent characteristics. This is a good solution to model intermodal transport, however, attempts to use this type of modelling in OmniTRANS did not succeed, but an alternative is found.

4.2.1. Building the infrastructure network and transit lines

The alternative way of modelling the container transport is based on the public transport class that is available in OmniTRANS. This class uses an access and egress mode, walking or car by default, to connect the origin and destination to the public transport network, that consists of bus, tram and train by default. The infrastructure network consists of connector links from each centroid to the road or walk links, a road network and a rail network. The service network is modelled by various transit lines, each with their own mode, speed, frequency and many more properties. In a normal public transport model, the lines are designed with a specific goal, but in this case, the lines are constructed in such a way that the complete infrastructure network is covered. When the network is completed, the generalised costs function can be set as a function of time, distance, waiting time, a penalty for transfers and a fare system. After completing all other requirements, a little script assigns passengers from an OD-matrix to the routes in the network with the lowest generalised costs.

Translating public transport network modelling possibilities into a container transport model does not require a lot of changes. The container takes the position of the passenger and the container needs to be transported along the route with the lowest generalised costs. Three of the five parameters of the generalised costs in OmniTRANS can be identified in the costs function in section 4.1.3: time, distance and the penalty of the transfer between lines. The waiting time and fare system are not used in the model so far. They could be used to increase the detail at terminals, or pricing specific links in the network.

The modes need to be translated as well. The rail and inland waterway modes are the transit modes, road transport is the walk mode. This way, it is possible to do a simultaneous route and mode choice. The road transport is modelled as the walk mode to use the OmniTRANS feature to look for "walk-only" paths as well, something it cannot do for vehicle transport. Fortunately, the cost function and speed of walking can be changed to the characteristics of road transport. However, there are two problems. Since it is only possible to have one access and egress mode for each load matrix, it is not possible to have EuroV, EuroVI and LHV's in the network at the same time, and pre- and end-haulage have the same characteristics as direct road transport. Not having the three trucks in the model is not a real big problem. The number of LHV's that transport containers is compared to normal trucks very low and the difference between a Euro V and VI truck is not very large in terms of fuel consumption and costs. Therefore it is decided that the model will only use Euro V trucks. The second problem is that the differences in costs between direct road transport and pre and end haulage. This is handled by a penalty on the links to the terminals. For every terminal the average pre and end haulage is estimated and the difference in costs with normal road transport is compensated by a toll fee. A list of the average pre and end haulage distances is available in Appendix V. The rail transport in the model will be done by electrical trains, due to a lack of information it was not possible to make a clear distinction between the use of rail network by diesel or electrical trains.

Building the network in steps

This section will show the construction of the network in the model. The first thing that needs to be done is defining the modes, means and means numbers, link types and numbers, and the speeds. The means that have a number that starts with a 3 are the transit means of mode 30 that use the transit-lines to transport the containers.

Table 4.9: The properties of the links

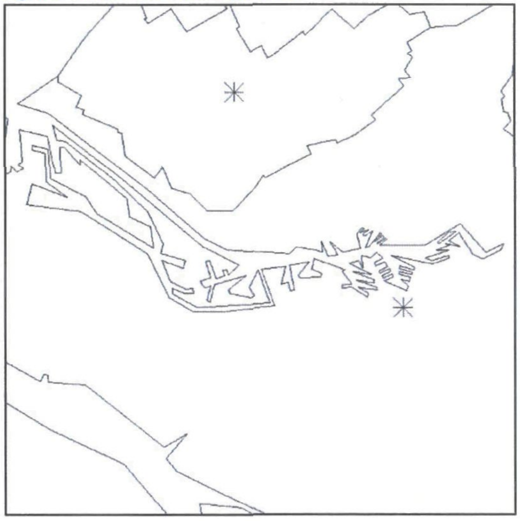
Type	Typenr.	Means	Speed [km/h]
Connector	0	40	50
Highway	10	40	50
Local road	11	40	30
Railway	20	34	40
Class II IWW	36	36	12
Class III IWW	37	37	12
Class IV IWW	38	38	14
Class Va IWW	39	39	14
Class VIb IWW	310	310	14

Step 2

Adding the areas and their centroid. The centroids are placed in the middle of the area when there was no large city in the area, or at the largest city of the region.

In figure 4.6, the city region of Rotterdam and the region of Westland are visible, the stars mark the centroid.

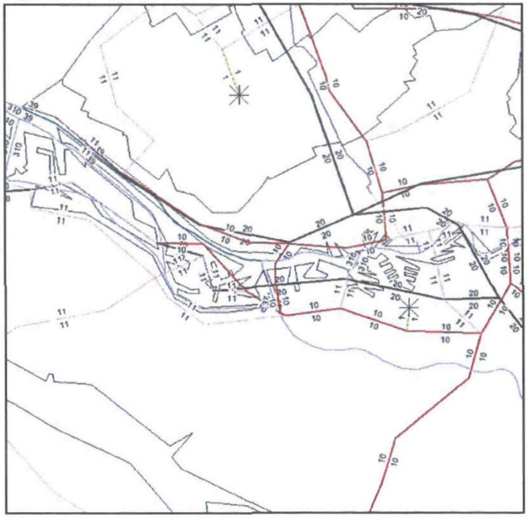
Figure 4.6: Areas and centroids



Step 3

Adding the road, rail and inland waterway networks as links. All link types have a predefined number, speed and mode that can use the link type, shown in table 4.9. The centroids are connected to the closest available road with a connector link.

Figure 4.7: Links

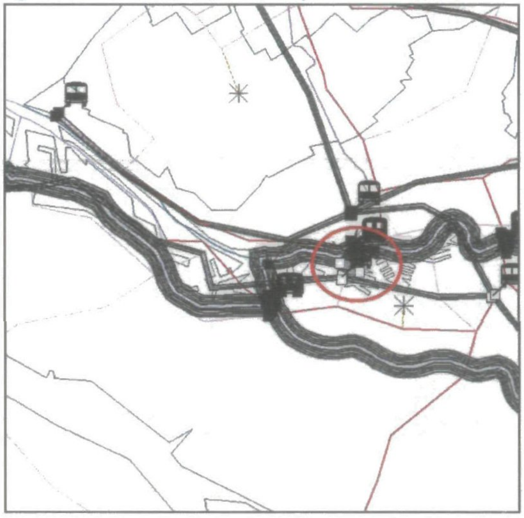


Step 4

Adding the transit lines on the rail and inland waterway links. Each means has its own transit line. Stops are added on junctions and at the terminal locations, at the terminal locations a transfer penalty is added. The terminal locations are connected to the road network.

Figure 4.8 shows the inland waterway and rail transit lines, some stops at junctions. The red circle indicates the locations of a rail and inland waterway terminal.

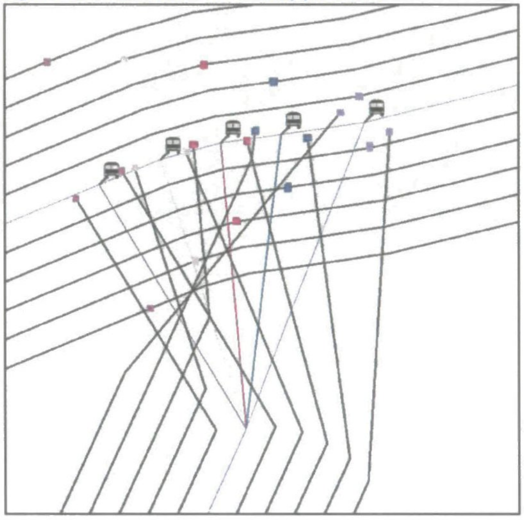
Figure 4.8: The transit lines, stops and terminals



Step 5

Fixing junctions where line to line transfers are possible. A transfer between two lines of the same means is allowed, since that is basically the same ship or train. Transfers between two different means are not allowed at normal junctions since it requires a terminal to tranship a container from one ship to the other.

Figure 4.9: An inland waterway junction



The complete network was built from available shape-files (TNO, 2010) which were processed in ArcGIS. The networks were checked on missing links and junctions, irrelevant dead ends and harbours were removed and the link types were set. After this process, the network was imported in OmniTRANS and checked again to make sure that the road network was not connected to the rail and inland waterway network. After that, the terminal locations are added to the networks and connected to the road network.

The network outside the Netherlands

To take the large flows from and to the Netherlands into account as well, the network needs to be expanded into the surrounding areas. This is done on a much lower detail level, only the most important links are modelled. The links that are used in the model are shown in table 4.10.

Table 4.10: Network outside the Netherlands

Highways to:		Rails to:	Inland waterways to:
Antwerp	Duisburg	Antwerp	Duisburg
Gent	Frankfurt	Paris	Basel
Bruxelles	Bremen	Duisburg	Bremen
Luik	Hamburg	Hamburg	Hamburg
Luxemburg	Berlin	Bremen	Antwerp
Paris	Poland	Poland	
South of France	Italy	Italy	

Terminals are placed at several locations along the rail and inland waterway network. The most important ones are in Antwerp and the Ruhr area.

4.2.2. The path building and assignment algorithm

The algorithm that is used by OmniTRANS assigns the traffic to the network in two steps. In the first step the path with the lowest generalised costs is constructed for each origin-destination pair. The second step is to assign the flows of containers to that path. The algorithm is a so called reverse propagation algorithm, which means that it starts at the destination and propagates backwards through the network of transit lines and stops.

Path building

Building the paths between the origins and destinations is performed in six steps that are used a couple of times to find the paths with the lowest costs, according to the cost function that has been defined in section 4.1.3.

Step 0 This is the initialisation of the process. A set of terminals that are connected to a destination is identified and the transport costs, including the transhipment costs, from these terminals to the destination are calculated and stored. If no stops are available in the range of the destination zone, all transport from and to that zone is done by direct road transport.

Step 1 In this step the algorithm searches for stops along the lines, which stop at the terminals of the previous step, where the line can be boarded. This can be either a terminal or a junction in the network where two lines of the same mode come together. For all possible boarding stops, the transport costs are calculated and the stops are added to a set of boarding stops.

Step 2 This step involves an important choice that has effects on the assignment algorithm. Using the 'standard' method, the probability of boarding a line is calculated based on the frequencies of the lines that are available at the stop. This means that when two lines are available, both with the same frequency, the probability of boarding one of the lines is 50%. The other possibility is to use the 'Zenith' method, developed by Veith Lister Consulting of Australia, which takes the transport costs from the stop to the destination and a line choice scale factor into account as well. Independent of the choice of the method, the algorithm continues by updating the transport costs from the stop to the destination and it calculates the stop costs, a value that is used in the final step. An explanation of the way the algorithm works can be found in the next section.

Step 3 Since there is a possibility that paths exist where separate parts of inland waterway or rail transport are connected by a part of trucking, the algorithm searches for those possibilities. This is done for the same stops that are used in step 2. If any additional stops are found, these are added to the set and taken into account in the next loop.

Step 4 The algorithm checks if a maximum number of interchanges is reached. If this is the case, it continues with step 5, if false, it returns to step one looking for routes with one more interchange.

Step 5 The final step is to find the terminals that will be used from each origin, the access candidates. Again, there is a choice between the 'standard' and 'Zenith' method. The 'standard' method chooses the terminal that has the lowest pre-haulage costs and the 'Zenith' method uses a logit function, based on the pre-haulage costs, line frequency and a scale factor.

The algorithm searches for paths until the maximum number of interchanges between transit lines is reached. If there is no path available, or when direct road transport is less expensive, the direct transport is chosen.

The 'Zenith' method in OmniTRANS

The 'Zenith' method is chosen for the line and stop choice, to take the availability of a line and the costs of different routes into account in the route and mode choice. The two parameters, one for the line choice and one for the access-stop choice, need to be determined. The formula to calculate the line choice probability is:

$$P_{l,s} = \frac{f_l * e^{-\varphi_l * C_{l,s}}}{\sum_{k \epsilon L_s} f_k * e^{-\varphi_l * C_{k,s}}}$$

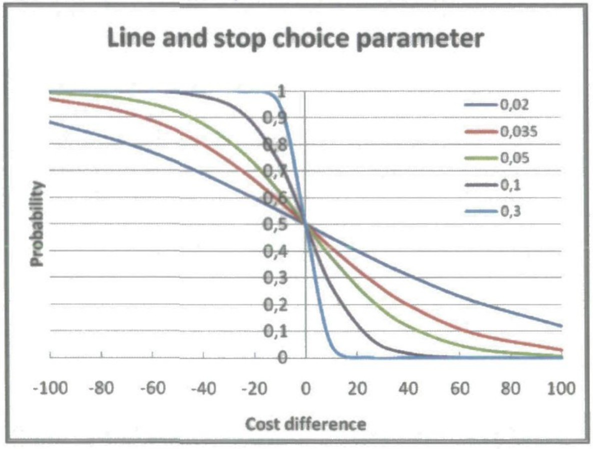
The probability of choosing line *l* at stop *s* from the set of lines L_s that stops at *s* is dependent on the frequency of line *l*, line choice parameter φ_l and the costs of the path when line *l* is chosen, $C_{l,s}$. The result is a probability that is dependent on an absolute difference in costs.

The access-stop, or loading terminal, choice, has a similar probability calculation:

$$P_s = \frac{e^{-\varphi_s * Y_s}}{\sum_{k \epsilon A_O} e^{-\varphi_s * Y_k}}$$

The probability of choosing stop *s* from the set of stops A_O, is dependent on the stop choice parameter φ_s and the costs of the path when stop *s* is chosen, Y_s. The influence of the parameter is shown in figure 4.10. The lines show the probability of choosing the line or stop as a function of the scale parameter and the cost difference with another line.

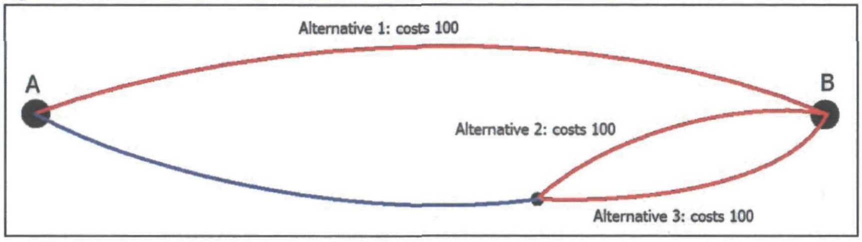
Figure 4.10: Line and stop choice as a function of the cost difference and scale parameter.



Choosing values for the stop and line choice scale parameter has a lot of influence on the model and represent shippers that do not make the same choice in the same situation. If a shipper wants his container shipped at a certain moment and the least expensive service is not available at that moment, he will choose a different service.

In both logit functions, there is a potential problem, because it relies on the independence of irrelevant alternatives (IIA). This assumption means that the probabilities of a route and mode choice are only dependent on the costs of the various alternatives. If three routes have the same costs, all three routes are assigned one third of the flow, even when two of the three alternatives are almost the same, this is illustrated in figure 4.11.

Figure 4.11: Illustration of three alternatives with identical costs



The IIA suggests that all three alternatives need to be considered at point A, while in practice the choice will be between alternative 1 and alternative 2 and 3. This results in a 50/50 choice at A and another 50/50 choice at the intermediate point. As a results, 50% takes alternative 1, 25% alternative 2 and 25% alternative 3. Unfortunately, it is not clear how OmniTRANS handles this.

Assignment

The containers in the OD-matrix are assigned to the paths in a couple of steps as well. This part of the algorithm works from origin to destination, a different direction than the path building algorithm.

Step 0 This step resets all the loads from previous runs and identifies the regions that have loads. The origin-destination pairs that have no demand are neglected.

Step 1 The algorithm recalls the access stops for a certain origin from the path building results and assigns the containers to the stops. The containers are divided over the stops depending on the stop choice probability. The results of this step are loads for every access stop that is used.

Step 2 For each access stop from the previous step the containers are divided over the lines that stop at the stop. This is done according to the line choice probability.

Step 3 The containers follow the line until it is cheaper to exit the line. This leads to two possibilities: the container is close to its destination and continues by truck, or it transfers to another line.

Step 4 The algorithm checks if all containers are assigned to the network and writes all the loads to the link network.

4.3. Calibration and validation of the model

To make sure that the model calculates the right things and has the right sensitivities to changes in the input, the model needs to be calibrated and validated. Calibration will be done by comparing the modal split and transhipment numbers to figures found on the terminal websites, validation is done by comparing the cost elasticities of the transport modes to figures found in literature.

4.3.1. Calibration

Comparing the output of the model to available statistical information about modal split and terminal transhipment numbers is necessary to assess the quality of the output of the model. The first thing that is done is a change in the speeds on the road. While the average speed of a truck in the Netherlands is 55 km/h, the speed on local roads in the model is changed to 30 km/h and on highways to 50 km/h. This is done because the model seemed to be very sensitive to the speed on the road, leaving it on 55 km/h resulted in a modal split that was almost 100% road transport. This is most likely caused by the absence of waiting times at terminals.

Assuming that the cost functions of the means, networks and origin-destination matrix are right, there are two more parameters that are suitable for the calibration process: the scale parameters of the logit functions for line and stop choice and the transhipment costs of the terminal. The scale parameters have influence on the shares of different routes between a certain OD-pair and therefore on the modal split. The transhipment costs are used because that is one of the few available sources to check the flows. A total of 16 terminals were found that publish transhipment numbers on their websites and will be used.

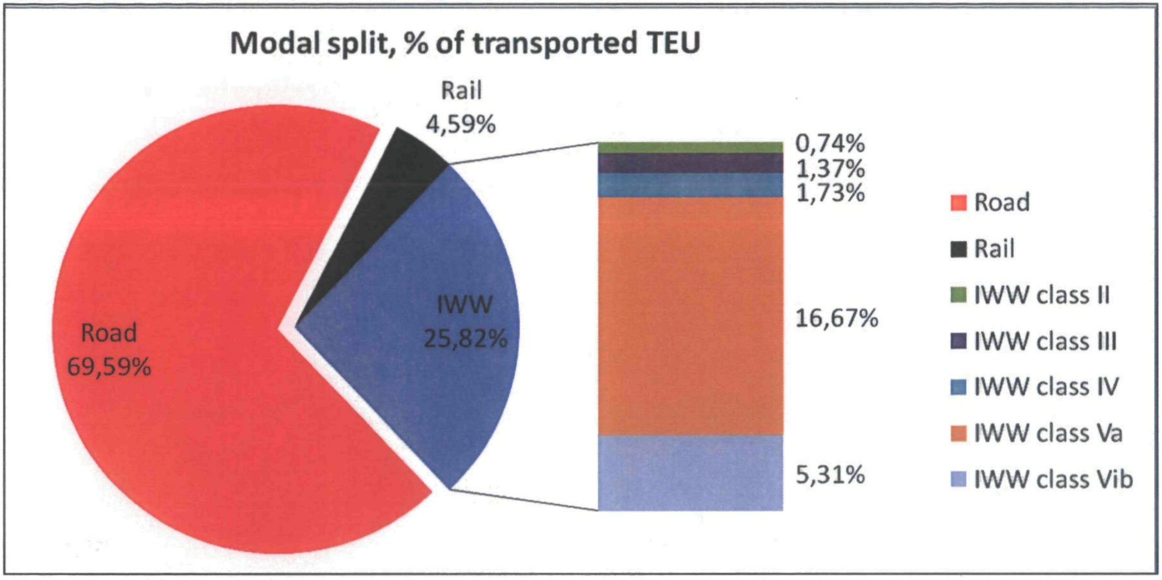
Changing the transhipment costs at the terminals showed that a change at a single terminal often influenced other terminals as well and that the modal split did not change significantly. Changing the scale parameters had more or less the same effect on all terminals and a lot of effect on the modal split in the network. Therefore it is concluded that the scale parameters are used to get the modal split in the right direction and after that the transhipment costs of the terminals are altered individually to improve the fit of the transhipment numbers.

Changing the scale parameters

As explained in the previous paragraph, the scale parameters determine the probabilities of choosing between routes with a certain difference in costs. After several attempts, it became clear that the modal split could not be matched with the numbers from section 2.4.4. This is most likely caused by the large flow to Germany, which is included in the model, but not included in the figures from the SOIT evaluation (Decisio BV, 2002). The resulting modal split figures are shown in figure 4.12.

The scale parameter that is chosen for the line choice is 0.015. Looking back at figure 4.10, it becomes clear that this is a rather low value, which means that when there is a large difference in costs between two alternatives, still both are assigned a certain amount of flow. In practice, this can be seen as a container that is transported in a certain way, simply because it is not possible to transport it differently. For the terminal choice, the scale parameter is 0,1; so a much smaller difference in costs leads to different choices.

Figure 4.12: Modelled modal split in percentage of TEU's



Changing the transhipment costs.

The start for the transhipment costs are the figures that were found in section 2.1.4, €35 per container for a rail terminal and €45 per container for a barge terminal. Looking at the range for the transhipment costs that is presented by Decisio BV (2002) of €14 to €68 per transhipment, it becomes clear that there can be large differences in transhipment costs between terminals and that is the reason to use the costs for the calibration step.

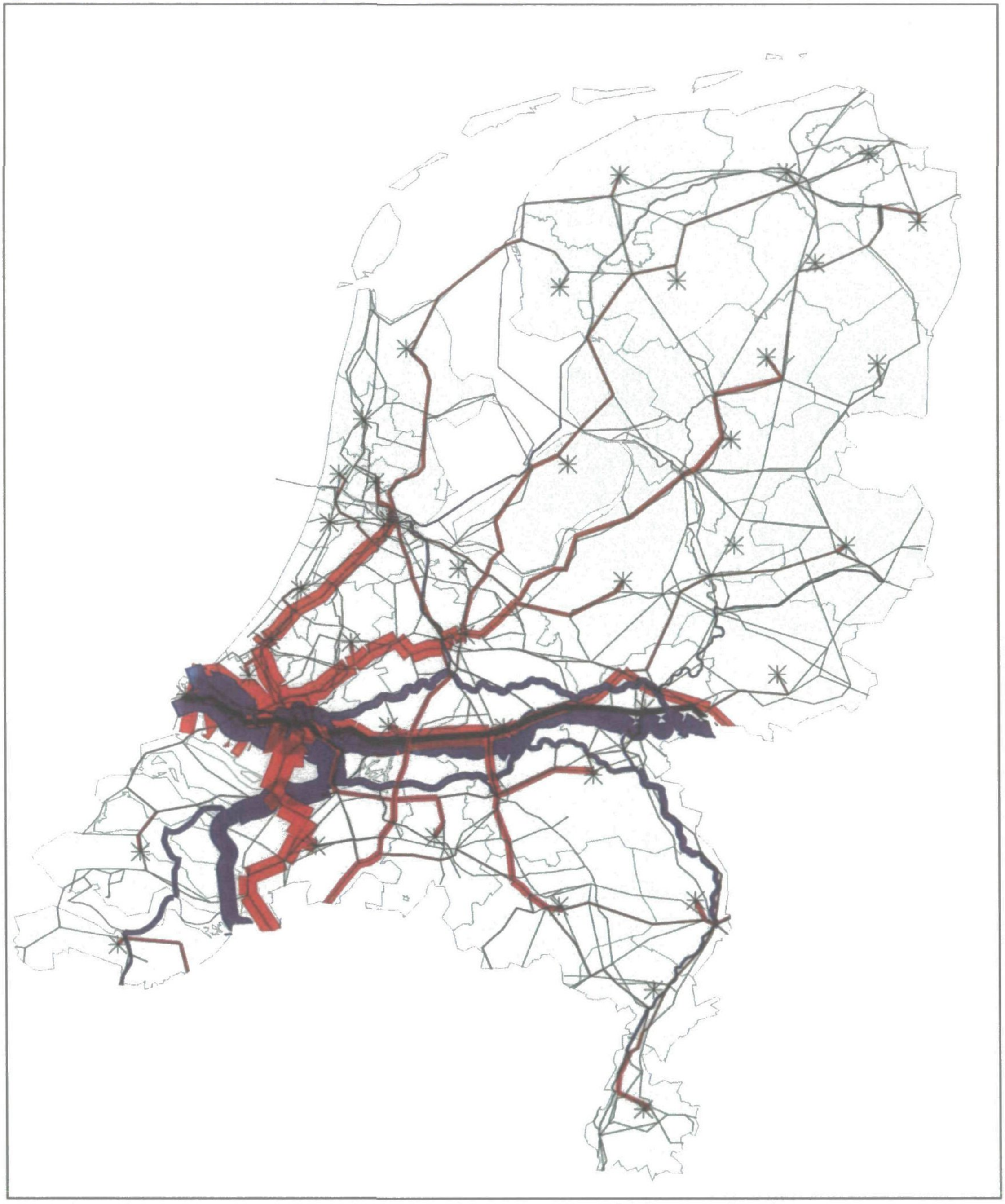
The costs are changed step by step and each time the transhipment numbers are compared to the actual numbers. A weighted average and standard deviation of the ratio between the modelled and actual numbers is calculated. After ten iterations a set of transhipment costs was found that results in an average ratio of 1,067 and a standard deviation of 0,266 and 15 terminals are within a standard deviation of the average. The average is a bit high and the deviation still large, but an additional iteration did not improve the results. An overview of the iterations can be found in Appendix X. The resulting transhipment costs are shown in table 4.11.

Table 4.11: Calibration of the transhipment numbers

Terminal number	Terminal place and type	Actual Transhipments [TEU]	Modelled Transhipments [TEU]	Transhipment Costs [€/TEU]
19	Moerdijk (Rail)	45000	45368	20,00
109	Groningen (Rail)	95000	85716	47,50
136	Moerdijk (Barge)	45000	38937	65,00
153	Vlissingen (Barge)	30000	24303	30,00
171	Den Bosch (Barge)	120000	140317	20,00
186	Harlingen (Barge)	6000	5713	90,00
192	Meppel (Barge)	27500	23559	81,30
194	Groningen (Barge)	22500	42858	225,00
198	Hengelo (Barge)	90000	91530	45,00
210	Born (Barge)	120000	114199	30,00
214	Venlo (Barge)	100000	119184	46,50
215	Venlo (Rail)	100000	114407	21,50
216	Amsterdam (Barge)	22500	18021	44,20
221	Wanssum (Barge)	95000	92252	17,50
226	Zaandam (Barge)	50000	41036	32,00
359	Nijmegen (Barge)	85000	94653	31,50

The barge terminal in Groningen shows a number of transhipments that is too high, while the transhipment costs are very high as well. The cause of this deviation is not found, there might be a mistake in the way the terminal measures its number of transhipments, or there might be an error in the model.

Figure 4.13: Modelled container transport in the Netherlands



Legend: Red is road transport, black is rail transport, and blue is inland waterway transport. The width of the bar is an indication for the amount of flow on the links

It becomes clear that most of the flows are oriented at Rotterdam. Another remarkable conclusion, although it is not visible in the map, is that inland waterway transport to Germany is done by two routes: Class Va ships take the Lek and Nederrijn, while the other ships follow the Waal. It is also found that class VIb ships are only used for the transport to Germany and not to Belgium. The last note is that rail transport only appears on the Betuwelijn.

4.3.2. Validation

After the calibration step, the output of the model has a sufficient match with the real situation. There is one more step that needs to be done and that is checking whether the model has the right sensitivity to changes in the variables. In this case, the costs of the transport means will be changed and a generalised cost elasticity and cross elasticity of each means will be calculated and compared to values found in literature. The formula to calculate the elasticity is:

$$\varepsilon_{i,j} = \frac{\ln(Q_{i1})-\ln(Q_{i2})}{\ln(P_{j1})-\ln(P_{j2})}$$ (M Beuthe *et a.l*, 2002)

This results in the elasticity between a cost difference in mode j and a demand difference in mode i. In their paper, Beuthe et al. present the elasticities that were calculated with the output of the NODUS-model. For all three transport means, the transport costs were increased by 5%, independent of each other. The same is done for this model, the results are shown in table 4.12, together with the results of NODUS.

Table 4.12: Comparison of the elasticities in the model and NODUS and Abdelwahab (1998)

Model				NODUS (aggregated)				Abdelwahab		
	Road	Rail	IWW		Road	Rail	IWW		Road	Rail
Road	-1,37	0,00	0,12	Road	-0.48	0.04	0.04	Road	-1.44	1.75
Rail	1,55	-1,31	0,09	Rail	1.95	-1.25	1.5	Rail	1.54	-1.88
IWW	3,94	0,24	-0,34	IWW	2.81	0.32	-1.44			

Legend: Cost changes are the columns, demand changes in the rows.

It becomes clear that there are differences between this model and NODUS, but that might be caused by comparing the wrong things. In the paper it is concluded that the elasticities are highly dependent on the geographical network and the initial modal split. For example, NODUS is focussed on Belgium, a country with a different modal split: 79,7% road, 9% rail and 11,3% inland waterway, while this model focuses on the Netherlands and has a modal split of 69,6% road, 4,6% rail and 25,8% inland waterway. The difference in initial modal split is to a large extent caused by the different geographical network in the two countries. Another cause of the difference is that the NODUS output is aggregated for all ten NST-R chapters, and our model is calculated for containers only.

While calculating the elasticities, it became clear that there were quite some differences in the results when different changes in costs were used. It seems that the elasticities are not constant, which is caused by discreet steps in the modal split when the costs are increased or decreased. The three charts on the next page show elasticities and cross elasticities for ten cost changes, from -25% to +25%, in all three modes independent. Road transport, figure 4.14, shows the largest variance in the elasticities and it should be noticed that the elasticity at -5% is the lowest value that does not follow the trend of the other numbers. The elasticity of rail transport, figure 4.15, shows a more or less constant trend, most of the flow is taken from, or lost to, inland waterway transport. Figure 4.16 shows that the elasticity of inland waterway transport is different for a cost increase than for a cost decrease.

Figure 4.14: Elasticity of road transport

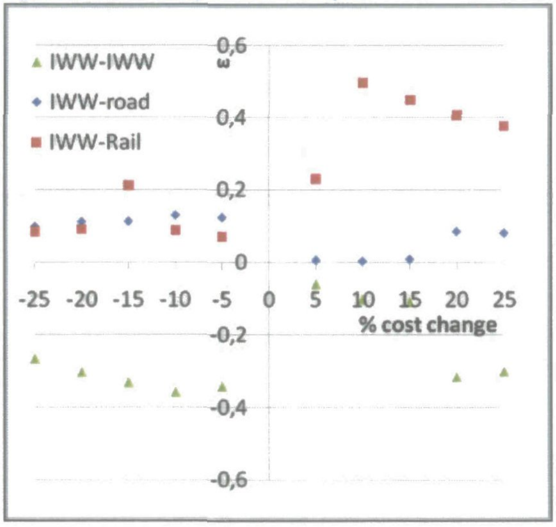


Figure 4.15: Elasticity of rail transport

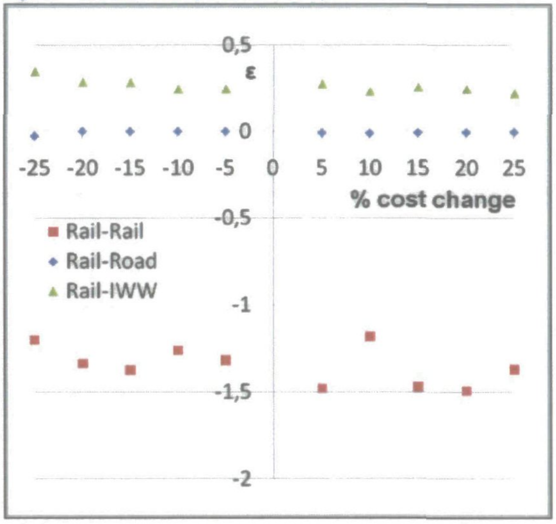
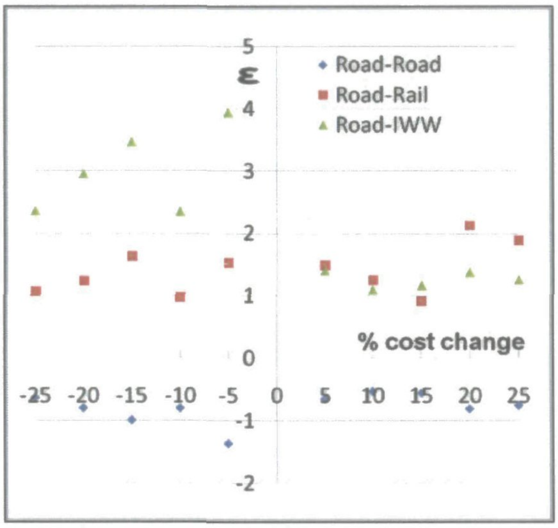


Figure 4.16: Elasticity of IWW transport



Another source provided aggregated price elasticities for road and rail transport in the United States (W. M. Abdelwahab, 1998), however, that is something different than cost elasticities, but a comparison is made. Since inland waterway transport is not included, the results are different, but comparing them shows that the three different approaches are within range of each other. A third source, (G P Geilenkirchen *et al.*, 2010) presented an overview of more than 10 different researches that all give numbers that are in the same range as the numbers derived from this model. It is therefore concluded that the model is sensitive enough to changes in the costs.

It is not possible to estimate the results of CO$_2$ pricing based on the calculated elasticities. This is because the elasticities are calculated in a ceterus paribus condition, so only cost increases in one of the modes. CO$_2$ pricing will influence the costs of all modes at the same time.

5. Analysis of the results

The previous chapter concluded with a model that creates sufficient output, and output for the reference scenario. This chapter will show and discuss the results for the various groups of scenarios that were described in the end of Chapter 3:

Group A:
- A range of CO_2-emission prices between €10 and €200 per ton.

Group B:
- B1: B30 biodiesel in road transport
- B2: B100 biodiesel in road transport
- B3: B100 biodiesel in road and inland waterway transport
- B4: An increase of the oil price of 100%

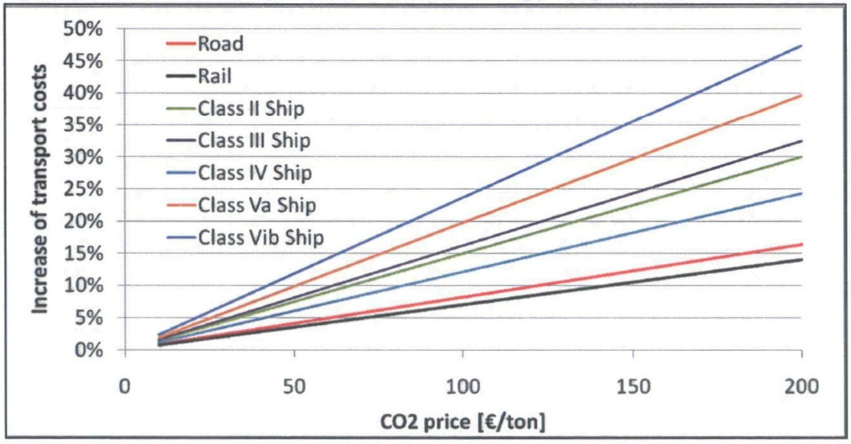
Group C
- C1: Additional rail terminal in Valburg
- C2: Barge shuttle service between the Maasvlakte and Alblasserdam

The results that will be shown and described are:
- Modal split
- Total CO_2-emissions
- Total costs
- Network use
- Changes in the transhipment numbers at the terminals

5.1. Scenario group A – CO_2 pricing

In this group of scenarios, only the price of a ton of CO_2-emissions is changed. This is done in steps of €10 in a range from €10 to €200. Before the results of the prices are shown, the increase of the costs of all transport means is shown in figure 5.1. It becomes clear that the costs of inland waterway transport have the largest relative increase, but in absolute values the increase is about five times lower than the increase of the costs of road transport.

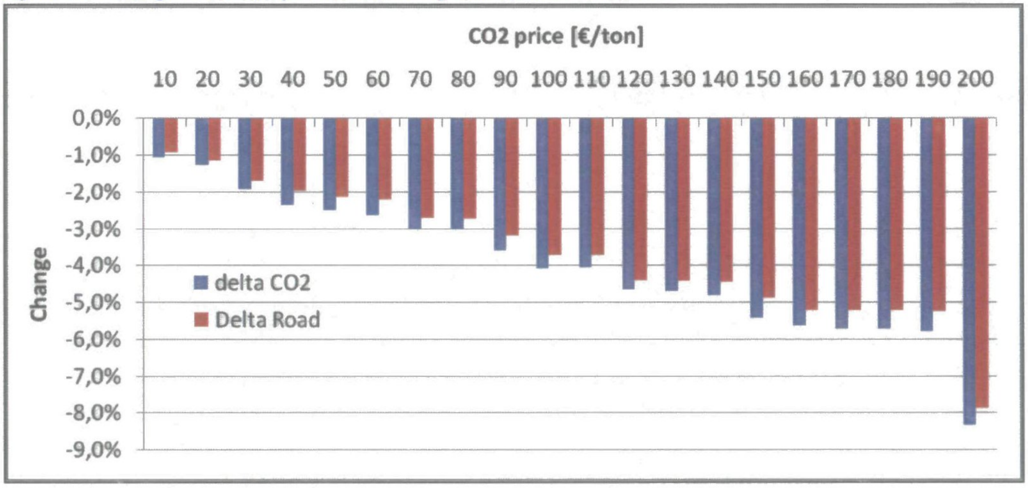
Figure 5.1: Increase of transport costs as a result of CO_2 pricing



The effect on the modal split

To show the effects of the increasing price, the modal shift from direct road to intermodal transport and the change in the total CO_2-emissions, the graph in figure 5.2 is made.

Figure 5.2: Change in modal split and total CO_2-emissions in scenario A



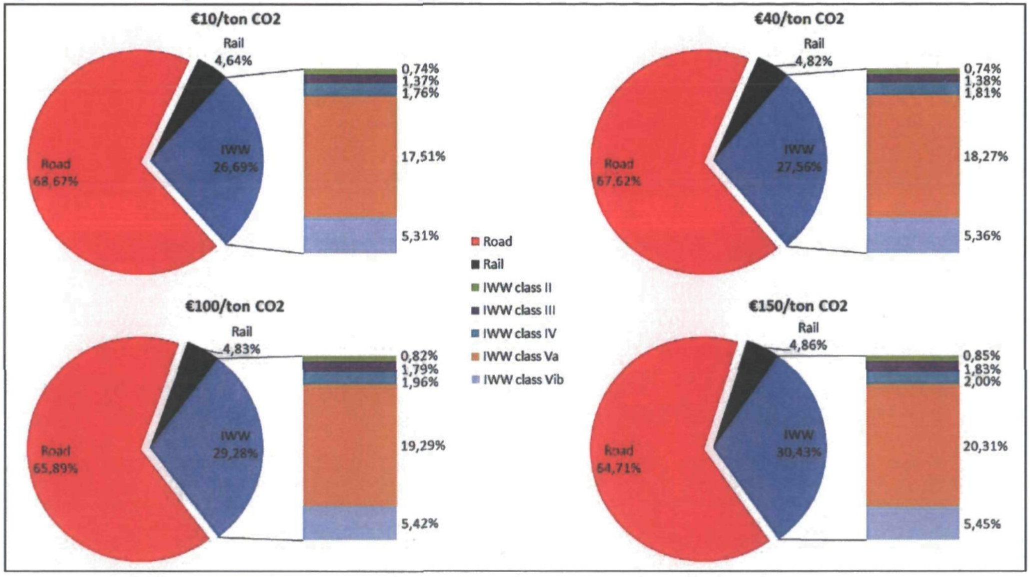
It becomes clear that the change in modal split occurs in steps. The largest step, at a CO_2 price of €200, is caused by a large modal shift in the flow from Rotterdam to the Ruhr-area in Germany. At this CO_2 price, the difference in costs between direct road and intermodal transport becomes that large that the logit function assigns all the containers to intermodal transport. Another remarkable thing is that the reduction in CO_2-emissions is almost equal to the reduction of direct road transport.

The four charts in figure 5.3 show the modal split that are the result of a CO_2 price of €10, €40, €100 and €150. These prices mark the step in modal shift and are therefore considered as useful prices, a price higher that the chosen ones will not lead to a significant change until the next step is reached. It is clearly visible that inland waterway benefits the most from CO_2 pricing, which makes sense because it is the mode with the lowest emissions per TEU-km.

It is also visible that rail does not really benefit from a CO_2 price higher than €40. The modal shift towards rail is 0,23% at that price, and 0,27% at €150. An explanation could be that rail transport is not as clean as inland waterway transport and that the pre and end haulage distances are larger. It is assumed that the extra demand on rail transport can be fulfilled by the existing services, which results in two extra benefits: lower costs per TEU and lower CO_2-emissions per TEU. So the effect of pricing CO_2 will even be larger than is presented here.

The different means of inland waterway also show some differences. When the CO_2 price is increased from €10 to €150, the relative increase of the percentage of TEU's that are transported by a Class III ship is 33,6%, while a Class VIb ship gains only 2,6%. For the fleet of class VIb ships, this means that the extra demand of around 30.000 TEU's can easily be handled by the existing fleet. For the Class III fleet, this might be different, because the extra 100.000 TEU's are unlikely to fit in the existing fleet. This creates a space in the market for new ships like the Neo-Kemp, which are class III ships. Just as for rail, this results in lower costs and emissions per TEU for most of the ship types.

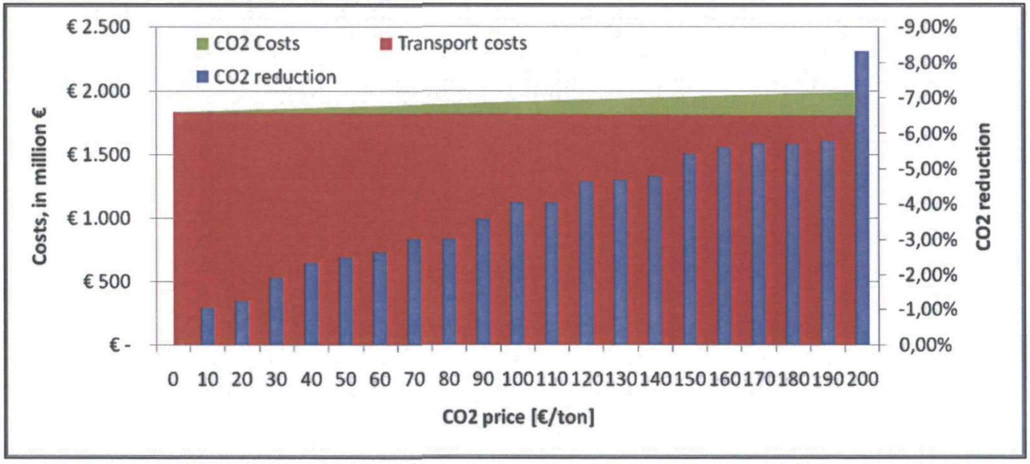
Figure 5.3: Modal split for four different CO$_2$ prices.



Effects on the costs and emissions

It is clearly shown that pricing CO$_2$-emissions cause a modal shift towards rail and inland waterway, and that it leads to lower total emissions. It does however come at a price, the transport of containers will become more expensive. An overview of the costs, together with the reduction of CO$_2$-emissions, is shown in figure 5.4.

Figure 5.4: The total transport costs, CO$_2$ costs and emission reduction in Scenario A



The current total costs of the container transport are around €1,84 billion when CO$_2$-emissions are not priced. This increases to €1,99 billion when a ton of CO$_2$ has a price of €200. The total costs of the CO$_2$-emissions are around €180 million, at the price of €200/ton.

Effects on the use of the network

The change in modal split is a result of a change in the use of the network. The maps in figure 5.5 to 5.8 show the changes in the use of the network in the Netherlands, larger maps are available in Appendix XII to XXI. The largest difference can be seen between Amsterdam and the border near Antwerp, where road transport becomes less popular. The difference on the corridor to Germany is smaller, it is assumed that this will show a large difference at €200 per ton, given the change in modal split.

Besides the effects on international connection, pricing CO_2-emissions has effects on the national connections as well. At a price of €10 per ton, not much changes, but at €40, the north of the Netherlands becomes more attractive for intermodal container transport. Looking at a price of €100, Limburg becomes more attractive as well, an increase of the flows on the Maas is clearly visible.

Effects on the terminals

The transhipment numbers at the terminals do not increase much. Only a couple of terminals experience large growth. The rail terminals in Ede, Leeuwarden, Groningen and Amsterdam show significant growth figures, but the price of a ton of CO_2 needs to be high. The rail terminal in Venlo even shows a decrease when the CO_2-price becomes higher than €100 per ton.

For the barge terminals the increase in transhipment numbers is rather low for a lot of terminals as well. The terminals in Amsterdam, Meppel, Harlingen, Kampen and Zaandam show an increase of more than 50% in the transhipment numbers. There are no barge terminals that have lower transhipment numbers when CO_2-emissions are priced.

Figure 5.5: Change in network use, CO_2-price €10

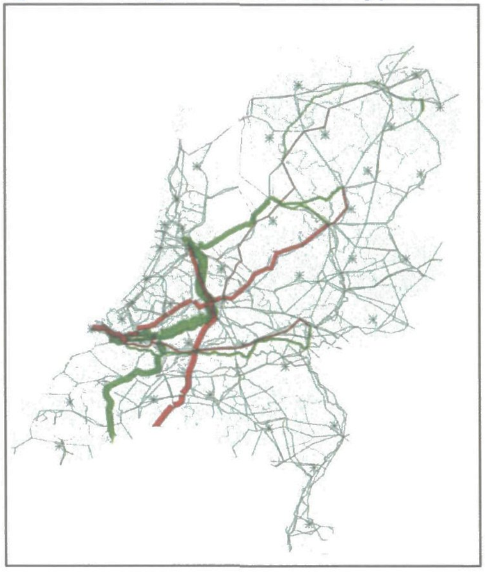


Figure 5.6: Change in network use, CO_2-price €40

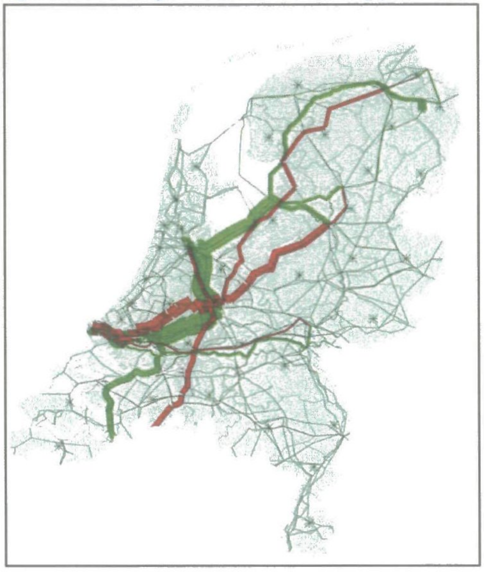


Figure 5.7: Change in network use, CO_2-price €100

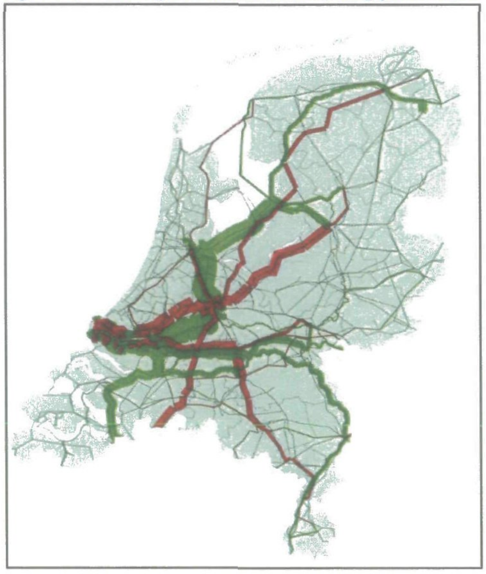
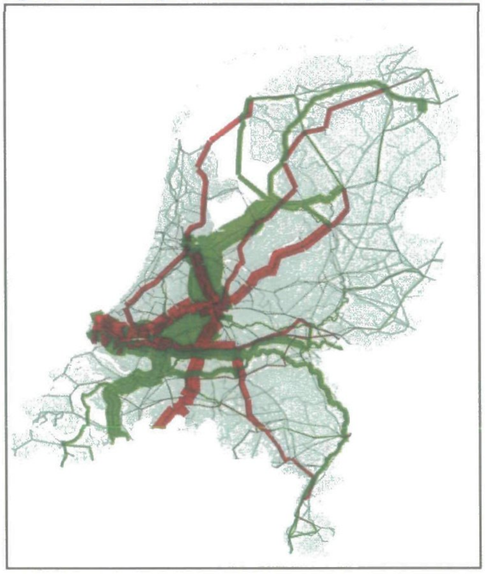


Figure 5.8: Change in network use, CO_2-price €150



Legend: Red is a decrease, green is an increase, the width of the bars is an indication for the relative change in the flow on the links

5.2. Scenario group B – Additional policy and developments

Changes in the energy source of container transport can have a large impact on the emissions. This paragraph focuses on the results of legislation that forces trucks and ships to use different types of biodiesel and also shows what happens when oil becomes twice as expensive.

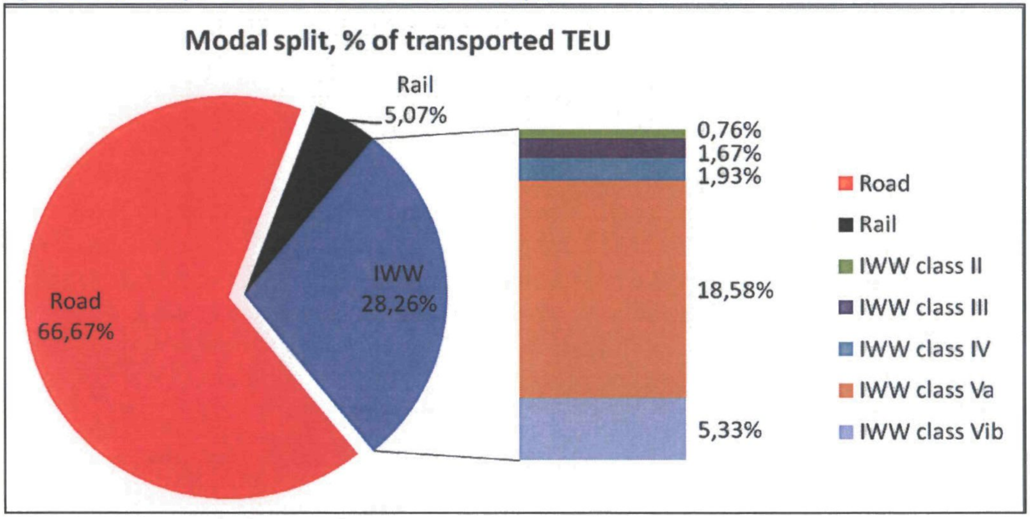
5.2.1. Scenario B1 – B30 biodiesel in road transport

B30 biodiesel is a mixture of 70% normal diesel and 30% biodiesel. This results in a reduction of CO_2-emissions of 20%, however, the fuel costs increase by 25%. This causes a modal shift when CO_2 is not priced and pricing will increase the modal shift. However, the effect of pricing will be smaller than in scenario group A, since the relative advantage of rail and inland waterway transport becomes smaller.

The effect on the modal split

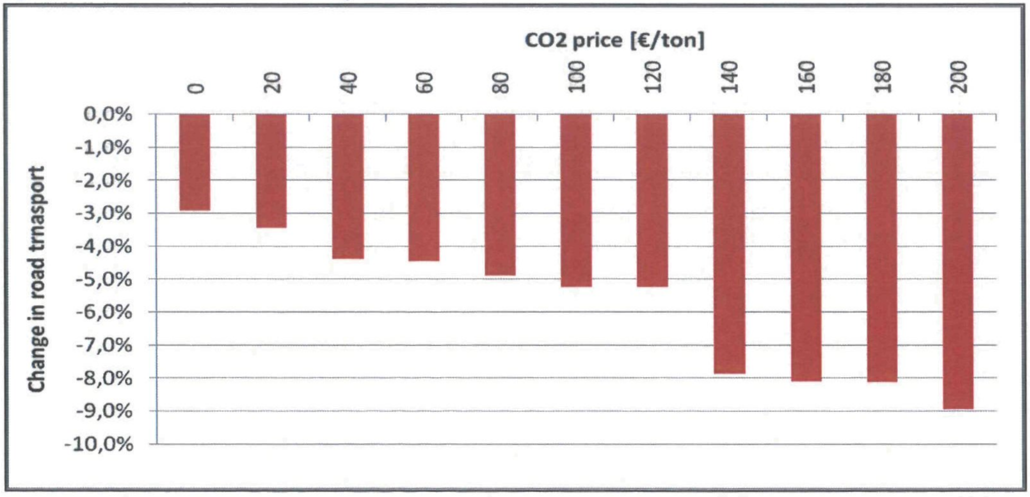
The modal split that is the result of forcing road transport to use B30 biodiesel is shown in figure 5.9. This shows that B30 biodiesel causes 2.9% less road transport, without using CO_2 pricing. The share of rail increases by 0,5% and the inland waterway share increases by 2,4%, which is mainly taken by class Va ships.

Figure 5.9: Modal split with B30 biodiesel in road transport



To show that the results of CO_2 pricing are different when biodiesel is used, a range of CO_2 prices is used to show the decrease of the emissions and the modal shift away from road transport.

Figure 5.10: Reduction of road transport in Scenario B1

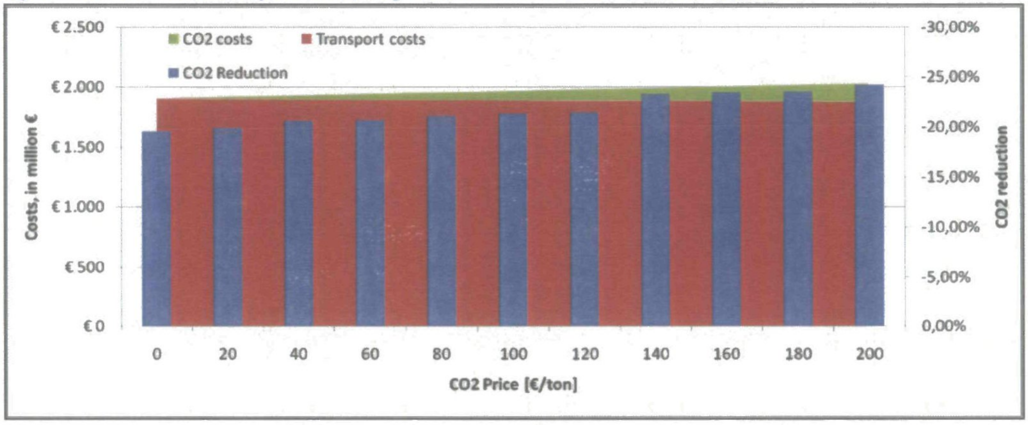


It is clear that the results of CO_2-pricing and the biodiesel, in terms of modal shift, are considerably larger when road transport is forced to use B30 biodiesel. This is caused by the price increase due to the B30 being more expensive than normal diesel. When the results of scenario group A are subtracted from the results in Figure 5.10, it becomes clear that the effects of pricing are smaller. At a CO_2 price of €100 per ton, the reduction of road transport is 3,7% when B30 is not used and only 2,3% when it is.

Effects on the costs and emissions

The effect that pricing has less influence on the modal split when B30 is used, is visible in the total costs and emissions as well. When the reduction of CO_2-emissions without pricing, almost 20%, is subtracted from the results with pricing, the reduction is smaller than in scenario group A.

Figure 5.11: The total transport costs, CO_2 costs and emission reduction in scenario B1



This graph reveals that the transport of containers became more expensive, but that a little less money is spend on CO_2-emissions. However, it reveals a more important effect of using B30 biodiesel, the reduction of CO_2-emissions is almost 20% when CO_2 is not priced. This is caused by the large reduction of the emissions of road transport. This leads to the conclusion that pricing CO_2 is not very useful when road transport is forced to use B30.

Effects on the use of the network

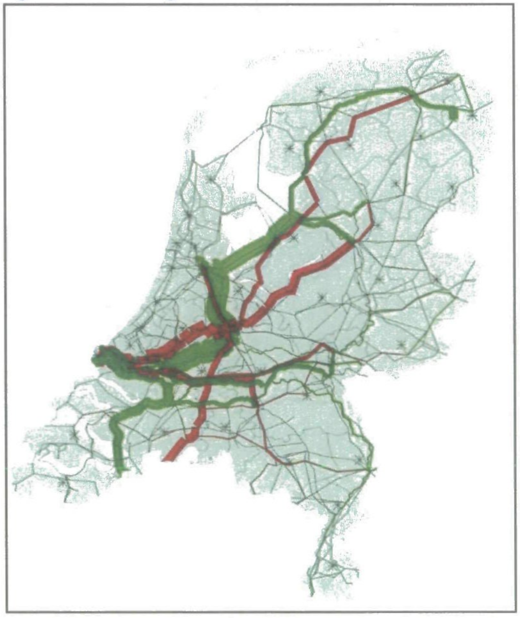
The increase in the costs of road transport shows a similar effect on the modal split as pricing CO_2-emissions at €60. Looking at the network use, the results look like the results shown in Figure 5.6. The north of the Netherlands shows more intermodal transport. Other small changes can be seen in the connection to Limburg and the area around Nijmegen.

Besides the strong focus on Rotterdam, the effects on the connection between Amsterdam and Antwerp are also visible. The transport to Germany does not change significantly.

Effects on the terminals

The transhipment numbers at the terminals show similar changes as in scenario group A, with only one important difference: there are no terminals that tranship fewer containers.

Figure 5.12: Change in network use in scenario B1



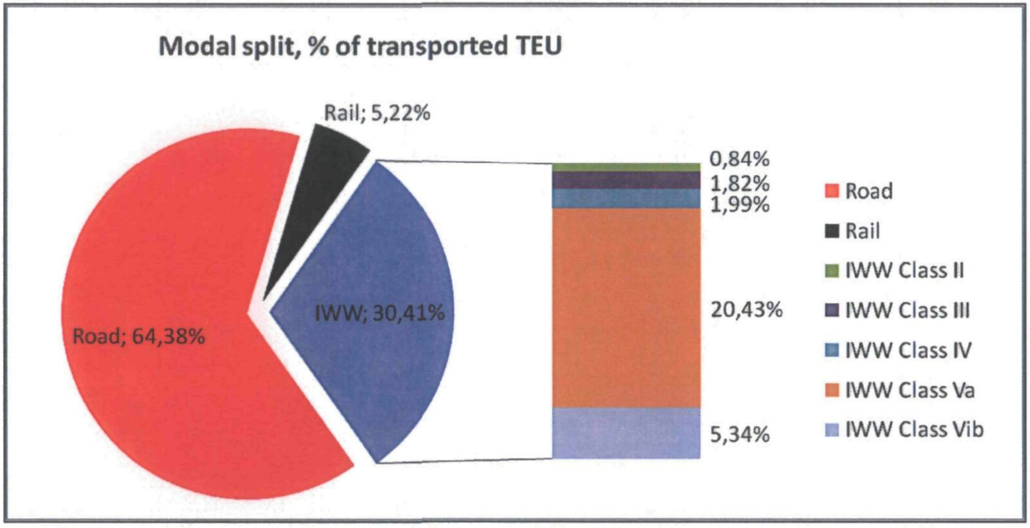
5.2.2. Scenario B2 – B100 biodiesel in road transport

Forcing road transport to use B30 biodiesel looked very promising, the total CO_2-emissions go down by almost 20%. When CO_2 is priced, this can increase to around 23%. To further improve the reduction, the price could be higher or a different fuel could be used. A diesel mixture with a higher percentage of bio content, will cause a further reduction. Assuming that the supply of pure biodiesel, B100, is sufficient for the demand of road transport, this scenario looks at the effects of pure biodiesel.

The effect on the modal split

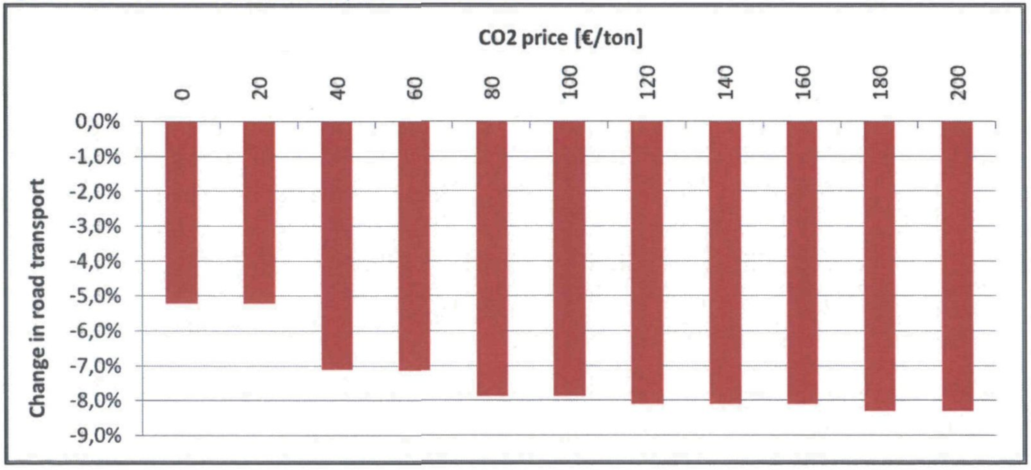
The modal split of this scenario, shown in figure 5.13, shows another 2,5% less road transport, most of that shift is now transported by inland waterway transport. More in detail, this modal split shows the same trend as in scenario B1; the increase in inland waterway transport is taken by class Va ships.

Figure 5.13: Modal split with B100 biodiesel in road transport



The effects of pricing shows the same trend as well, the effects become smaller when the emissions become more expensive. Figure 5.14 shows that the modal shift has almost the same size for the price range between €80 and €200 per ton.

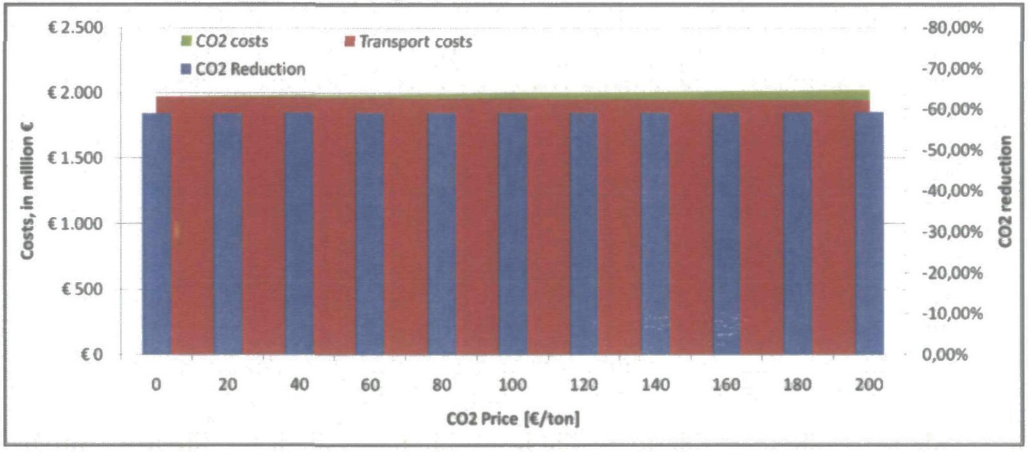
Figure 5.14: Reduction of road transport in scenario B2



Effects on the costs and emissions

The emissions show a very large reduction, which is caused by the reduced emissions of road transport. The results of pricing the emissions is less than expected, the reduction caused by pricing is almost zero. The reason for this is that a truck that runs on B100 has almost the same emissions as a train or inland ship. Therefore, the increased fuel costs cause a modal shift, but an increase in CO_2 price does not lead to larger relative cost differences.

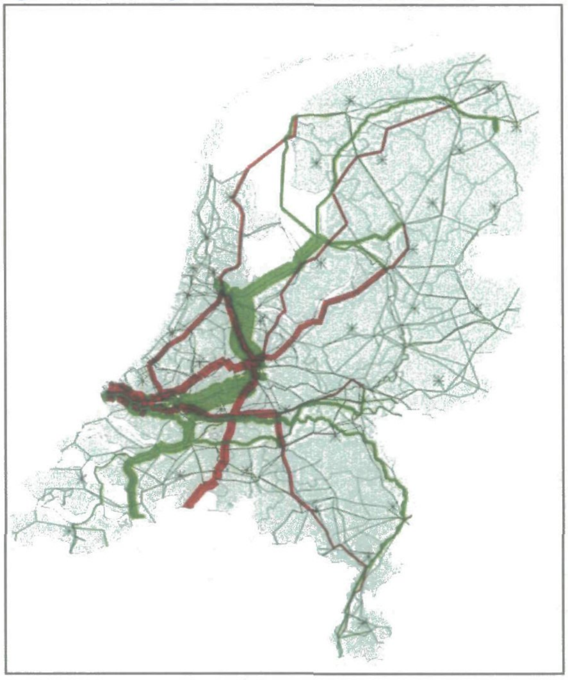
Figure 5.15: The total transport costs, CO_2 costs and emission reduction in scenario B2



Effects on the use of the network

Making road transport even more expensive has a lot of effects on the use of network. The map in figure 5.16 shows changes in almost every direction. The width of the bars is scaled down by a factor 4 when compared to the previous figures, because the effects are much larger.

Figure 5.16: Change in network use in scenario B2



In this scenario, the road connection between Amsterdam and Rotterdam is used less, which is not only caused by the transport to the north of the country, but by direct transport between Amsterdam and Rotterdam as well.

Effects on the terminals

There is one terminal that will tranship much less containers as a result of the biodiesel, the rail terminal in Oss has 80% less transhipments. The rail terminal in Venlo also has lower numbers, around 27%. The rail terminals in Tilburg, Leeuwarden and Amsterdam, and the barge terminals in Meppel, Amsterdam, Kampen and Zaandam more than double their numbers.

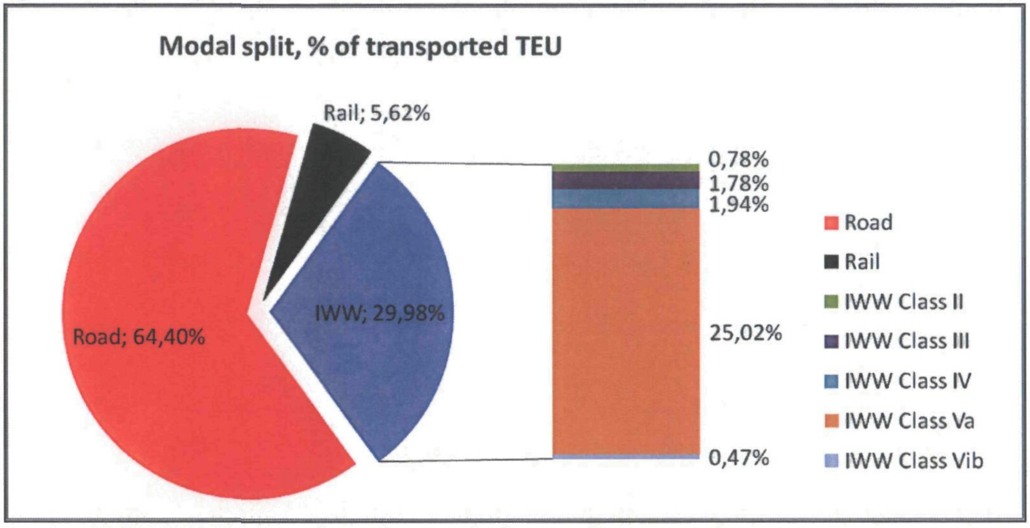
5.2.3. Scenario B3 – B100 biodiesel in road and IWW transport

The last that could be done with biodiesel, is forcing inland waterway transport to use B100 as well. In this case, the reduction of CO_2-emissions will be at least 68%, but it is less certain what happens to the modal split, because inland waterway transport becomes more expensive.

The effect on the modal split

The increase in costs of inland waterway transport causes a modal shift towards road and rail transport. The increase in road transport is very small, but the share of rail relatively increases by almost 10%. It is also clear that the largest inland ships are no longer used, the fuel efficiency of the class Va ships is better, so they take the share of class VIb ships.

Figure 5.17: Modal split with B100 biodiesel in road and IWW transport

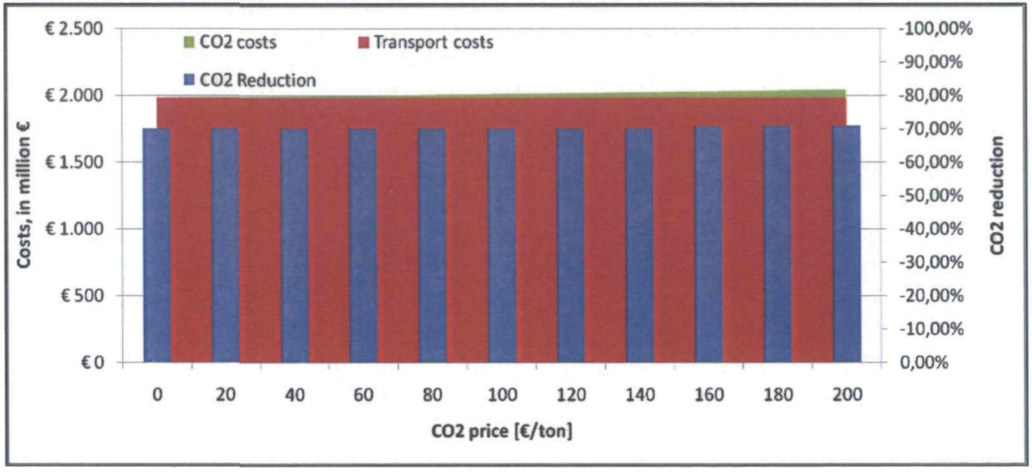


With the effects of B100 in road transport only in mind, it is expected that the modal split will stay constant when CO_2-emissions are priced. The difference in emissions becomes that small that only CO_2 prices higher than €140 per ton cause a modal shift that is larger than half a percent.

Effects on the costs and emissions

Because there is no longer a significant modal shift when the CO_2 price becomes higher, the reduction of the emissions does not become larger either. This is shown in figure 5.18, the reduction of CO_2 is around 70%. The total costs do become larger, but the total CO_2 costs are much smaller than in the other scenarios.

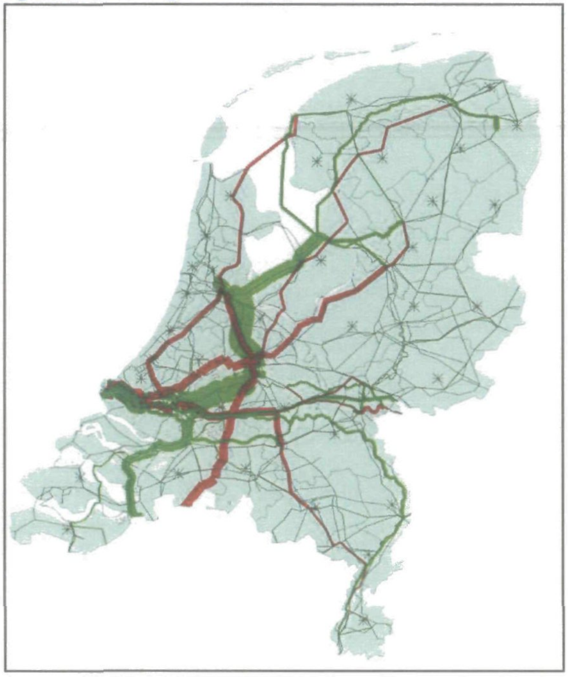
Figure 5.18: The total transport costs, CO_2 costs and the emission reduction in scenario B3



Effects on the use of the network

Comparing figure 5.19 to figure 5.16 reveals that not much changes in the network use either. It is concluded that forcing inland waterway transport to use B100 as well, does not lead to significant changes. The only noticeable difference is on the Amsterdam-Rijn Canal between the Nederrijn and the Waal, more ships choose the route on the Nederrijn instead of the route on the Waal.

Figure 5.19: Change in network use in scenario B3



Effects on the terminals

The rail terminal in Venlo benefits from the extra costs for inland shipping to the barge terminals in the region. The transhipment numbers are 8% higher than in the reference scenario. Most of the other terminals have transhipment numbers that are in the same range as in scenario B2, some of them are a few percent lower, like the rail terminal in Groningen and the barge terminals in Moerdijk, Groningen and Tilburg. Others, like the rail terminals in Rotterdam and Ede, and the barge terminal in Meppel have small increases in the transhipment numbers.

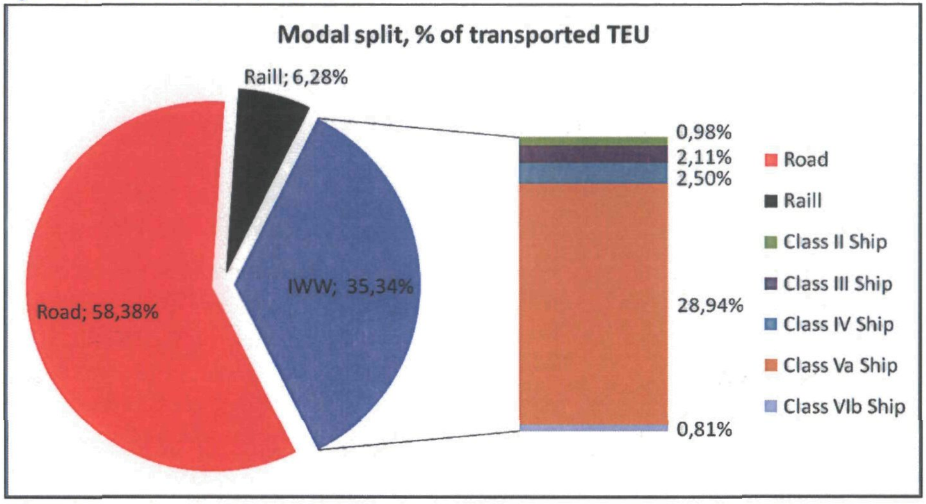
5.2.4. Scenario B4 – Oil price increased by 100%

An increase of the price of oil will have influence on the fuel costs of the carriers. Since the fuel costs of road transport are higher than the other two modes, a modal shift is expected.

The effect on the modal split

In figure 5.20, it becomes clear that a large increase of the fuel costs causes a large modal shift, 11,2% of the containers is no longer transported by truck. It is also shown that not much containers are transported by class VIb ships anymore, something that happened in scenario B3 as well.

Figure 5.20: Modal split of scenario B4



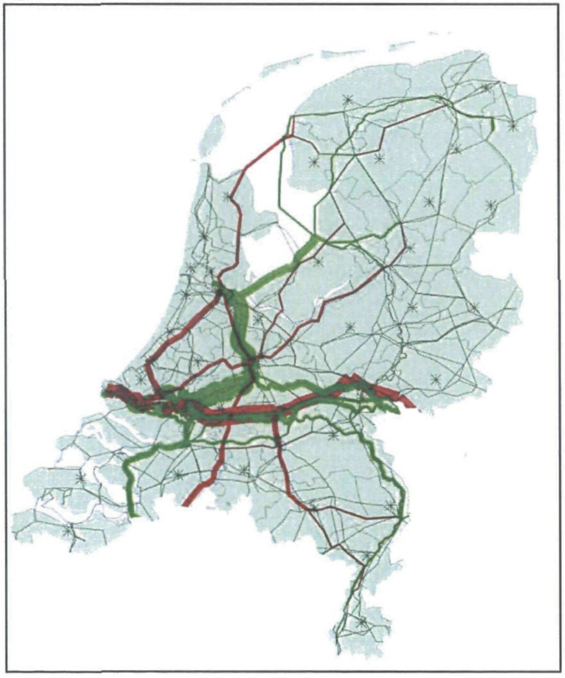
Effects on the costs and emissions

The total costs of the transport in the network increase by 12% when oil becomes twice as expensive. Following the modal shift that occurs, the total emissions are reduced as well, almost 13% less CO_2 emissions are the result.

Effects on the use of the network

Looking at figure 5.21, three important changes are recognised. The first one is a difference in mode choice in the corridor to Germany. The flow on the A15 goes down, while the flow on the Waal and Nederrijn increases. The second one is the flow between Rotterdam and Amsterdam and the third is the flow from Amsterdam to Antwerp. This means that the three largest flows in the network will experience significant changes when the oil price doubles. The flows from Rotterdam to the north of the country change as well, but those flows are much smaller.

Figure 5.21: Change in network in scenario B4



Effects on the terminals

As can be expected from the network use, the terminals in Amsterdam, Zaandam and Rotterdam have increased transhipment numbers. However, the port area in Moerdijk also shows a large increase in the numbers. Both the rail and barge terminal more than double the transhipment numbers. The barge terminal in Utrecht also benefits of the new situation, the transhipment numbers double as well.

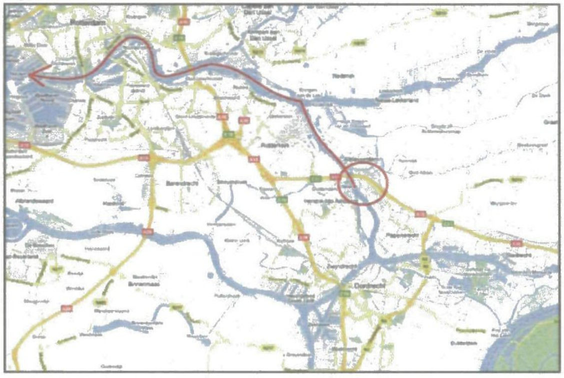
5.3. Scenario group C – Changes in the network

The last group of scenarios takes a different approach to change the use of the network. It is achieved by changing the network itself. The first change is the addition of a barge terminal in Alblasserdam, which is only used by a shuttle service to the terminals on the Maasvlakte. The second change is a rail terminal near Nijmegen.

5.3.1. Scenario C1 – Adding a shuttle service R'dam←→Dordrecht

As a start, the shuttle service was implemented as a class Va ship that only stops at the terminal at the Maasvlakte and the new terminal near Dordrecht. The location of the new terminal is shown in figure 5.22. Unfortunately, the service was not chosen by the model when the costs are equal to the costs of the normal inland waterway transport. The service competes with direct road transport from the Maasvlakte to regions around Rotterdam and Dordrecht. The transport costs of the shuttle are rather low, but the extra transhipment costs can never be compensated on the small distance. Another reason is that the pre and end haulage distances from and to the Maasvlakte are not much different than the distances from and to the new terminal. To make the shuttle service a feasible option, the speed of the service is enlarged to 18 km/h and the transhipment costs at the new terminal are reduced to €20 per TEU. After these measures, the new terminal is able to reach almost 50.000 transhipments.

Figure 5.22: Location of the new terminal



The results of adding the shuttle service can be divided in two, the results on the area around Rotterdam and the results on the complete network. The latter, the results on the complete network, are limited. Only 0,2% of the containers are transported by the shuttle service, which causes no significant changes in the total costs, emissions and modal split. For the region of Rotterdam there are more interesting results. The changes are shown in figure 5.23.

Figure 5.23: Detail of change in network use in scenario C1

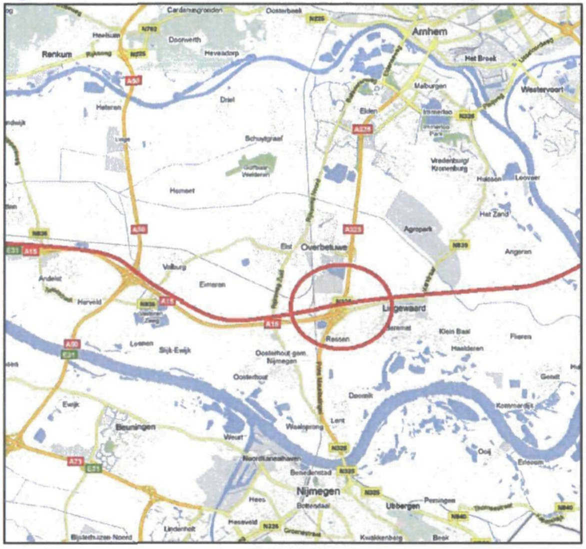
The use of the network around Rotterdam shows some remarkable changes. More containers are transported over the A15, the opposite of one of the goals of the shuttle service. The roads around the terminal become busier as well, although the change in the total traffic will be very limited (on average 3 trucks per hour).

The main conclusion after adding the terminal to the network is that it is too close to Rotterdam, it will only be used when something changes drastically in the transhipment costs and speed.

5.3.2. Scenario C2 – Adding a rail terminal in Valburg

The results of scenario C1 were marginal, no significant changes occurred for the whole network, and the traffic situation around Rotterdam did not improve either. The second scenario with an added terminal is one with a rail terminal in Valburg, near Nijmegen. A new barge terminal is already available in Nijmegen, but a rail terminal along the Betuwelijn might cause a boost in intermodal container transport to that region. It might be possible to have the same function as the ECT terminal in Venlo has at the moment. The location is chosen close to the end of the A15, see figure 5.24. The transport costs of the service do not need to be lower than the costs of all other services. The transhipment costs at the terminal are kept at €35 per TEU.

Figure 5.24: Location of the terminal near Valburg



Looking at figure 5.25 shows that there are changes in the network use. Rail transport that uses the new terminal is favoured above inland waterway transport that uses the terminals in Wanssum, Hengelo and Kampen. This results in a modal split that has more direct road transport, which is caused by the line choice probabilities calculated by the logit model and the competition between rail and inland waterway transport. The changes are however not very large, only 22000 TEU are transhipped at the new terminal. The resulting modal split is 70,3% road, 4,9% rail and 24,8% inland waterway transport. As a result of this, unfortunately, the total CO_2-emissions rise by half a percent. The total costs do not change significantly.

Figure 5.25: Change of network use in scenario C2

5.4. Summary of the results

To summarize the results of all scenarios that have been used, Table 5.1 is made.

Table 5.1: Summary of the results

Scenario	CO_2 price [€/ton]	Modal split			CO_2 reduction	Cost increase
		Road	Rail	IWW		
Reference	0	69,59	4,59	25,82		
Group A	20	68,44	4,65	26,91	1,26	0,91
	40	67,62	4,82	27,56	2,35	1,79
	60	67,39	4,68	27,92	2,64	2,61
	80	66,87	4,77	28,83	3,01	3,47
	100	65,89	4,83	29,28	4,06	4,35
	120	65,21	4,81	29,98	4,65	5,21
	140	65,15	4,79	30,06	4,80	6,07
	160	64,37	4,84	30,79	5,63	6,91
	180	64,37	4,82	30,83	5,71	7,75
	200	61,73	5,20	33,07	8,33	8,56
B1	0	66,67	5,07	28,26	19,57	3,78
	20	66,15	4,99	28,85	19,91	4,43
	40	65,21	4,97	29,82	20,64	5,10
	60	65,15	4,94	29,90	20,68	5,79
	80	64,71	4,99	30,29	21,13	6,48
	100	64,37	4,99	30,64	21,37	7,16
	120	64,37	4,98	30,65	21,46	7,85
	140	61,73	5,39	32,88	23,34	8,51
	160	61,50	5,38	33,11	23,52	9,15
	180	61,47	5,33	33,19	23,58	9,77
	200	60,65	5,39	33,96	24,19	10,41
B2	0	64,38	5,22	30,41	58,89	7,36
	20	64,38	5,18	30,44	58,90	7,65
	40	62,49	5,58	31,93	59,08	7,93
	60	62,45	5,55	32,00	59,07	8,20
	80	61,72	5,53	32,75	59,13	8,48
	100	61,72	5,49	32,79	59,15	8,75
	120	61,50	5,49	33,01	59,17	9,03
	140	61,50	5,45	33,04	59,19	9,30
	160	61,50	5,39	33,10	59,19	9,57
	180	61,30	5,34	33,36	59,22	9,82
	200	61,29	5,31	33,40	59,22	10,09
B3	0	64,40	5,62	29,98	70,11	8,08
	20	64,38	5,57	30,05	70,12	8,39
	40	64,38	5,44	30,19	70,13	8,72
	60	64,38	5,28	30,34	70,17	8,99
	80	64,38	5,24	30,39	70,15	9,31
	100	64,38	5,21	30,41	70,16	9,64
	120	64,38	5,18	30,44	70,17	9,97
	140	64,37	5,16	30,47	70,17	10,30
	160	62,13	5,59	32,28	70,76	10,62
	180	62,10	5,56	32,33	70,91	10,94
	200	62,09	5,53	32,38	70,93	11,27
B4	0	58,38	6,28	35,34	12,82	13,81
C1	0	69,81	4,61	25,80	0,00	0,03
C2	0	70,25	4,92	24,83	-0,49	0,09

6. Conclusions and discussion

This last chapter will present the conclusions that can be drawn from the results of CO_2 pricing in container transport. Besides that, the results and the model will be discussed. The last paragraph makes some recommendations to future research.

6.1. Conclusions

To be able to answer the research question, the first three sub-questions and goals will be answered or elaborated. The effects of pricing CO_2-emissions can then be stated, the effects of other policy measures are stated after that. Finally, a general conclusion about the possibilities to reduce CO_2-emissions is drawn.

Conclusions of the first three sub-goals

- *Build a GIS-based model to quantify, visualise and evaluate Dutch container transport.*

The model that has been built in OmniTRANS has proved to be a useful tool in quantifying and visualizing the effects of the different scenarios that were used. The short calculation time of less than 10 seconds makes it easy to assess the effects of the different measures. The model has been calibrated by comparing modal split and terminal transhipment figures. This resulted in a modal split of 70 road, 5 rail and 25 inland waterway transport and transhipment numbers for 16 known terminals that are within 20 of the figures reported by the terminals. The sensitivity of the model to changes in the transport costs are in the same range as found in literature.

- *Differentiate the characteristics of the modes into more detail than is done in found policy evaluation.*

Differentiating the characteristics of the modes is found not to be difficult, the way they are used was more difficult. Dividing road transport into three different types of trucks was possible, but using them at the same time in the model was not possible. The algorithm that was used only worked with one road transport means at the time. For rail transport it was possible to use two types of trains, with diesel or electrical traction, at the same time. However, making a division in which type of train is used on which track and modelling what happens when a train switches traction at a shunting yard, could not be done accurately. Therefore it was chosen to use electrical trains only. For inland waterway transport this division was made easily, the class of the waterway determines the highest class of inland ship that can use the waterway.

- *Identify, choose and evaluate a possible structure for emission pricing in the container transport sector.*

Since there is a direct relation between the fuel consumption and CO_2-emissions of a vehicle or ship, it is chosen to introduce a pricing system that works as a tax on the fuel. For rail transport this is more difficult, because it is not always clear what energy source is used to create the electricity that the train uses. A system that registers the emissions of rail transport needs to be created to have a fair system of pricing CO_2-emissions.

Main conclusions of the effects of CO_2 pricing on container transport in the Netherlands

The large difference in CO_2-emissions of road, rail and inland waterway transport causes a change in modal split towards the modes with lower CO_2-emissions when the CO_2-emissions are priced. However, when the price of a ton of CO_2-emissions is equal to the current price of CO_2-emission rights in the European Trading Scheme, which is around €15 per ton, the total amount of emissions goes down by only 1. At higher prices, the effects are larger; at €200 per ton, the reduction of the total amount of emissions is 8.4. As a result of the money that is spent on the emissions, the total transport costs increase by almost 10. It can be concluded that pricing CO_2-emissions causes a decrease in total emissions and that the higher the price, the higher the reduction. Increasing the price of CO_2-emissions does not always result in a reduction of the amount of emissions. It has been shown that the reduction increases in steps that are not linear to the steps of the price. Only when an increase in the CO_2 price results in a different mode choice for a significant amount of origin-destination pairs, the result is visible. For example, the difference in the total CO_2-emissions between €40 and €60 per ton, is only 0,2, while the difference between €60 and €70 per ton is 0,5.

The third conclusion is that the reduction of emissions is almost equal to the reduction of the road transport share in the modal split. This looks like a coincidence, but in fact it is not. Almost 90 of the emissions are caused by road transport and 95 of that is caused by direct road transport. When the share of direct road transport decreases, the share in the emissions decreases as well. However, the emissions of the other modes increase, so the total reduction of the emissions is slightly lower than the reduction of the share of road transport.

Conclusions of other CO_2-emission reducing measures

Besides pricing the CO_2-emissions, the effects of changes in the network and using different energy sources are investigated as well. The changes in the network, made by adding terminals, did not lead to significant changes in the network use, costs and emissions. A new barge terminal in Alblasserdam, with a shuttle connection to the Maasvlakte, attracted only 40.000 TEU per year. Adding a rail terminal along the Betuwelijn near Valburg resulted in 22.000 transhipped TEUs at the terminal, but the modal split shifted towards direct road transport by 0,8. As a result, the emissions and costs increased. It is concluded that adding terminals to the network does not lead to significant changes in the use of the complete network, but that the results on a smaller scale might be useful.
The results of different energy sources are more important. New regulations that force road transport to use different types of biodiesel leads to very large reductions of the total emissions. Not only causes it lower emissions of the carriers, it also causes an increase of the costs of road transport, leading to a modal shift towards rail and inland waterway transport as well. The reduction of CO_2-emissions is almost as large as the reduction of the emissions of road transport. Depending on the type of biodiesel, and the way the reduction of emissions is defined, the reduction of the total amount of CO_2-emissions can be as large as 68. This is much larger than the realistic reductions that can be achieved by pricing the emissions. The effects of pricing the emissions when biodiesel is used are smaller than when it is not, this is caused by the smaller difference in emissions of the modes.

Final conclusion

Pricing CO_2-emissions leads to a more efficient use of the available container transport system, however, reducing the CO_2-emissions of road transport leads to a larger reduction of the total emissions. The latter could be achieved by regulations that oblige road transport to use biodiesel.

6.2. Discussion

This discussion contains two parts: one that discusses the way the model was created and the implications of the assumptions that had to be made; the second part discusses the results.

The model

Using a model to assess the effects of future policy always has its limitations. One of the most important ones is that a model can be calibrated to the current situation, as long as there is sufficiently comparable data available from the real situation. When this is the case, the input and model together lead to the right output. This does however not guaranty that the model has the right response on changes in the input. Comparing the results of changed input to the reality is practically impossible in transport models. The number of variables is simply too large. The sensitivity of this model to changes in the transport costs has been compared to a number of sources that are often based on models as well. This comparison showed that the sensitivity was sufficient.
One of the most important assumptions regarding the input is that the model makes its choices based on costs instead of price. It was assumed that the margins between costs and prices are small, but in practice that is not true. The price that is asked by a transporter for a certain shipment is depending on a lot of components like the batch size, the situation in the market and the relation between the shipper and transporter. Some of the transporters will offer services below their cost level to attain a certain position in the market, while others are having a hard time and really need to make money.
Another input that has a large influence on the model is the origin destination matrix that is used. Although the underlying database is the one of the best available sources, container statistics are

very difficult. Since the database focuses on transport flows from and to the Netherlands, freight that is transported from a foreign country to for example Germany via the port of Rotterdam, is possibly not included in the matrix. This is an input that requires more research to improve the quality of the model.

The results

Pricing CO_2-emissions in container transport might lead to a reduction of the CO_2-emissions of container transport, however, it could also lead to a different development. A lot of containers are loaded with almost finished or finished products, which can be transported in normal trucks as well. As long as normal trucks do not have to pay for their emissions, they will be cheaper than container trucks. This could lead to new business activities in Rotterdam, unloading the containers and loading the freight in normal trucks and then transport it by road directly to the final destination. This results in less intermodal transport and therefore higher congestion and emissions. So CO_2-pricing could work, but only when it is implemented in the whole transport sector.

For inland shipping there is a potential problem in pricing CO_2-emissions or forcing the use of biodiesel. According to the 'Act of Mannheim' of 1868 (CCR, 2010), it is not allowed to change or introduce regulations that influence the principal of free freight flows on the Rhine. This is the reason that inland ships can use 'red' diesel (diesel without additional duties). So at a national level it is simply not possible to change something for inland waterway transport. This is one of the reasons to introduce CO_2 pricing at a European level.

There is another important motivation to introduce pricing on a European level. Pricing on a national level in the Netherlands could seriously damage the position of the port of Rotterdam. When the hinterland connections in Germany, Belgium and France would be much cheaper than the connections from Rotterdam, it is likely that a lot of shippers and transporters choose routes that do not visit Rotterdam as an intermediate port.

6.3. Recommendations to future research

Details in the transport modes are obtained in this research, however, it was not possible to include all the details in the model, due to a lack of time. It has been shown that there is a large difference in the costs of an inland ship that sails in deep water and a ship that sails in a shallow canal. This could be integrated in the model by creating separate modes for the different types of waterway and upstream and downstream directions. It is also recommended to include locks and bridges that need to be opened in the model, since that takes a lot of time.

A differentiation between diesel and electrical trains should be made as well. It has been found that diesel traction is mostly used in the port areas and that electrical traction is used for longer distances, however, this was not included in the model. The number of road transport means was limited by the capabilities of the software, but it should be possible to have separate means for the different types of trucks and the different types of transport, direct road or pre and end haulage.

Something that has not been included in the model either, are the waiting times that carriers experience at origins, destinations and terminals. The first two may be difficult to include, the last one could be implemented quite easily. Doing this results in a more accurate simulation of the travel times, which results in more accurate transport costs.

The last recommendation is about the value of time. The chosen structure to include value of time makes the value of time dependent on the mode that is used, while in practice it is a property of the freight inside the containers. It would be valuable when the value of time is represented as a property the containers, possibly in groups with a certain range of values. This is, however, only possible when sufficient data is available.

Regarding the scenarios, there are a couple of recommendations. This research focused on the use of diesel or biodiesel, while there are developments for other energy sources. Hybrid trucks with the same working principal as the Toyota Prius and the use of natural gas in road and inland waterway transport can lead to significant reduction in the emissions.

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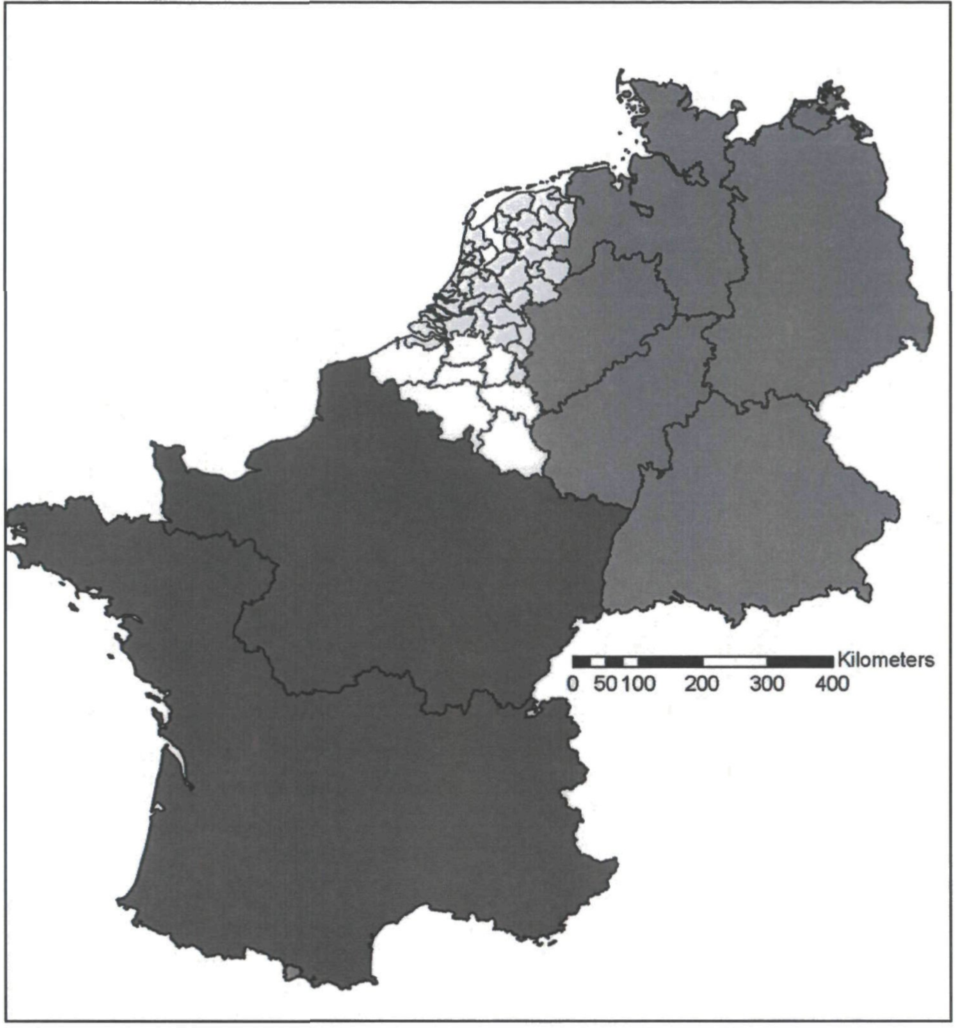
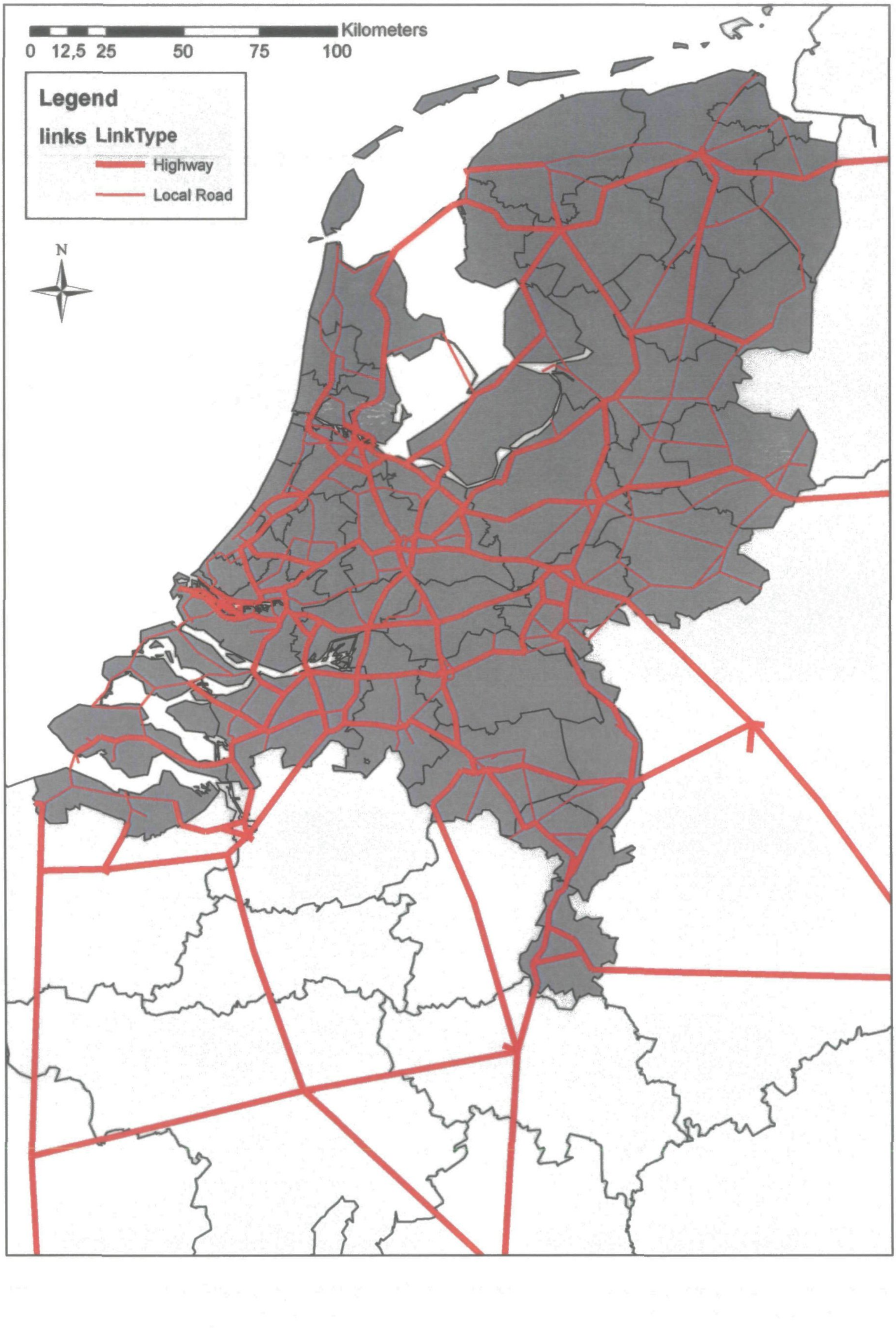
A. Appendices

I. Map of regions

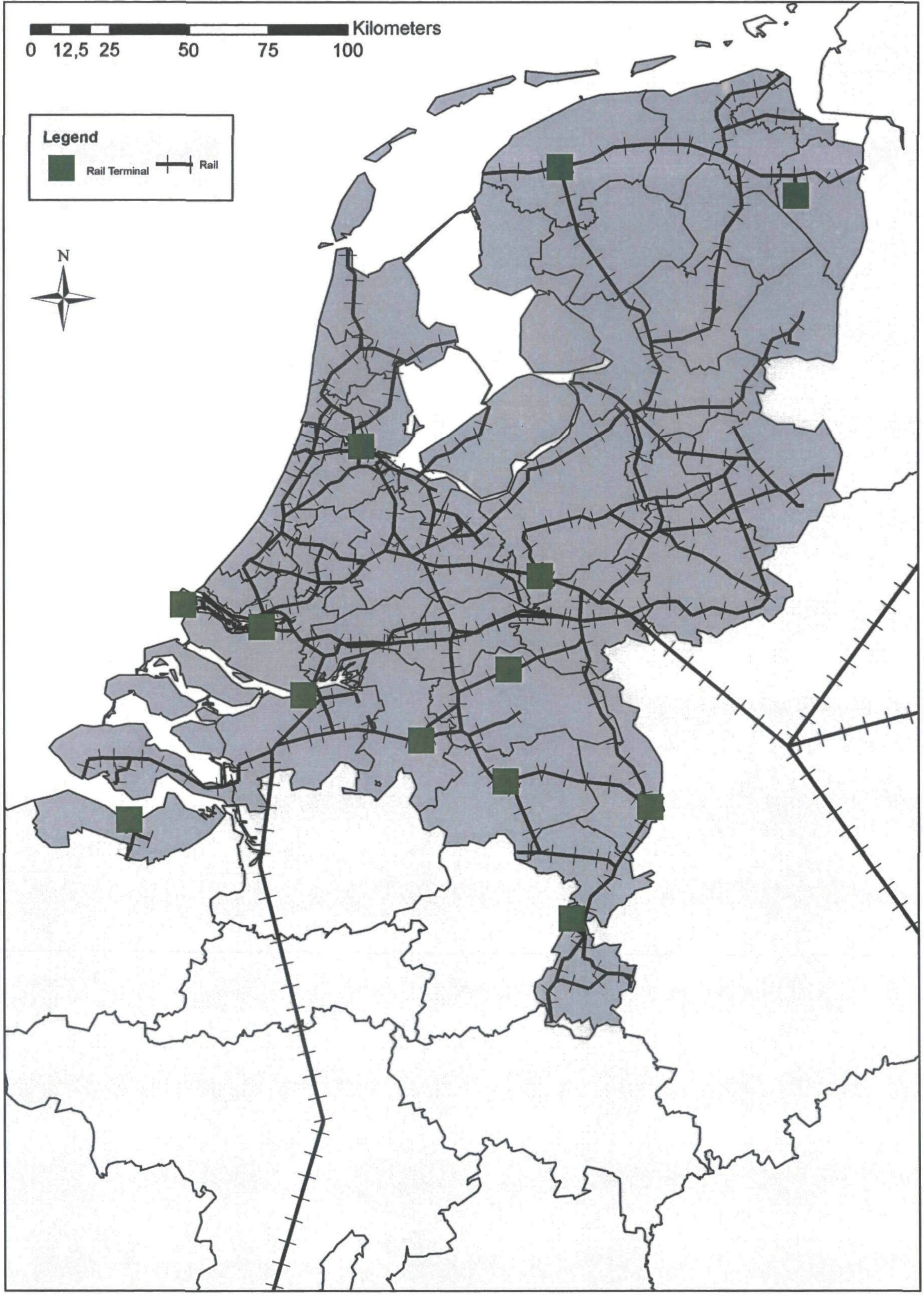


NL111	NL212	NL321	NL334	NL422	BE22
NL112	NL213	NL322	NL335	NL423	BE24+10
NL113	NL221	NL323	NL336	DE9+F	BE31+32+35
NL121	NL222	NL324	NL341	DE5	BE33
NL122	NL223	NL325	NL342	DE6	BE34+LU00
NL123	NL224	NL326	NL411	DE7+B+C	FR1+2+3+4
NL131	NL225	NL327	NL412	DE1+2	FR5+6+7+8
NL132	NL226	NL331	NL413	DE8+3+4+D+E+G	PL (not on map)
NL133	NL230	NL332	NL414	BE23+25	IT (not on map)
NL211	NL310	NL333	NL421	BE21	

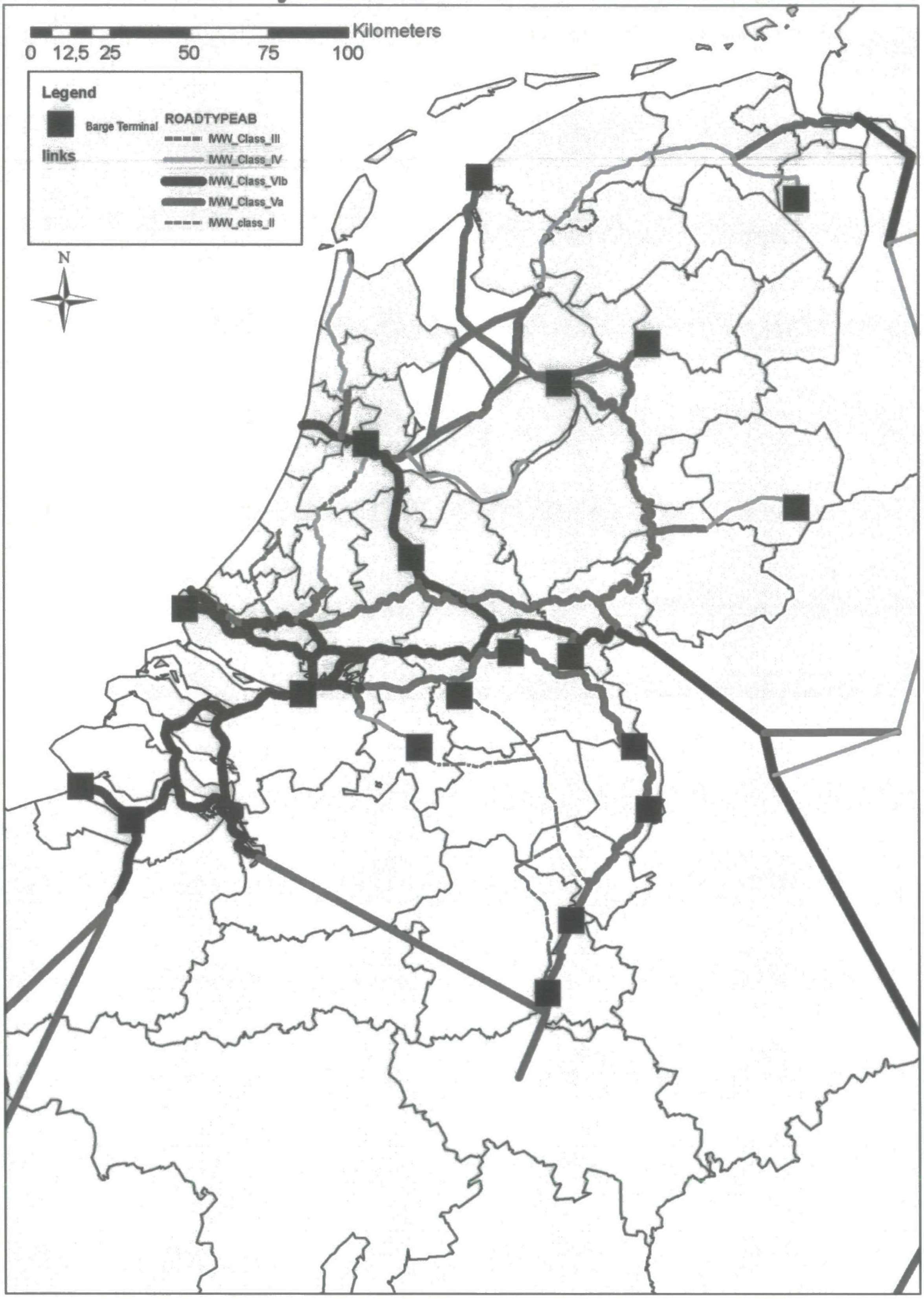
II. The road network of the Netherlands



III. Railway and terminal network of the Netherlands



IV. Inland waterway and terminal network of the Netherlands

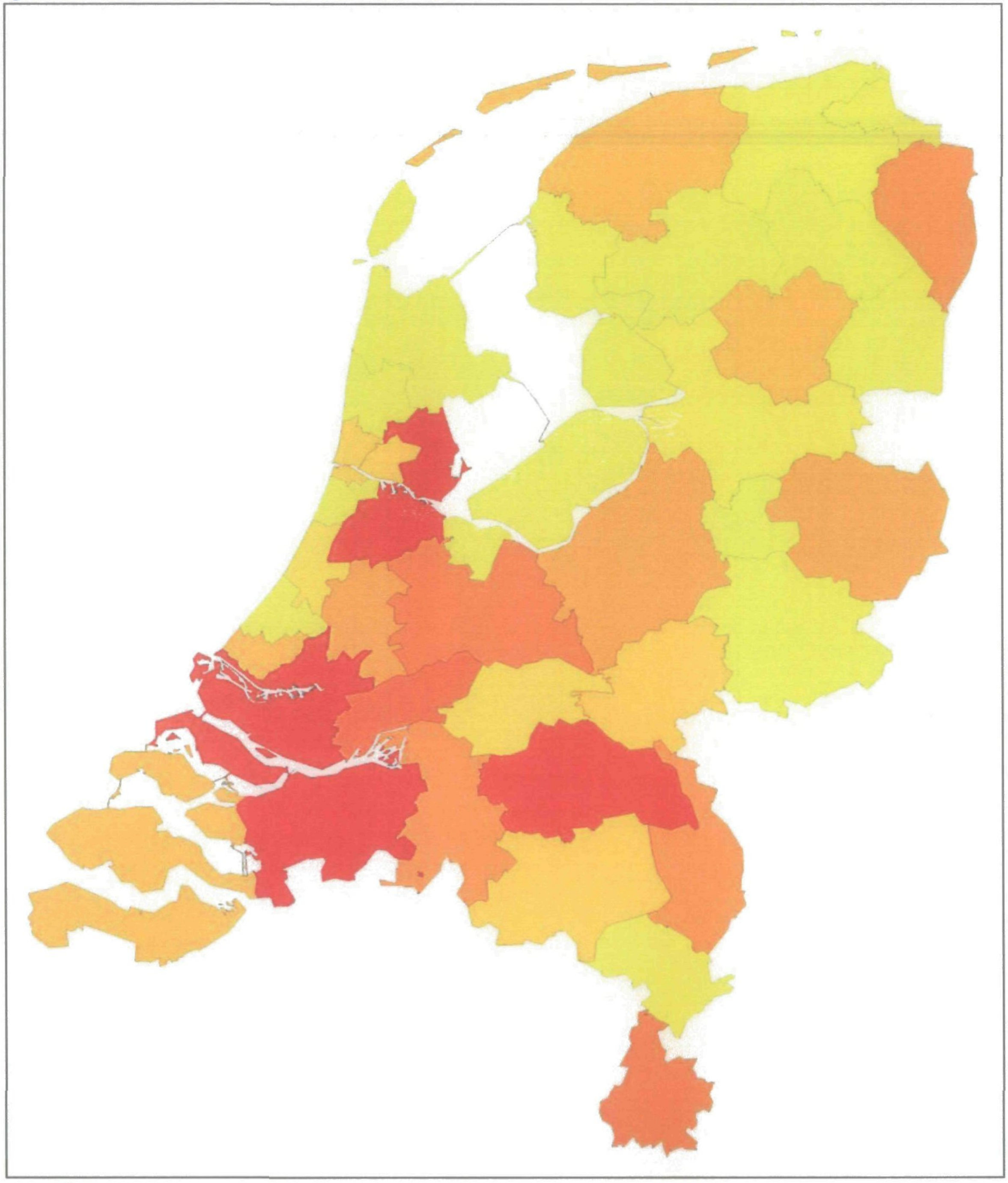


V. List of terminals

Terminal	Location	Type	Transhipment costs [€]	Nr. in the model	Pre and end haulage distance [km]	Transhipment-numbers in reference scenario
RTT	Tilburg	Rail	35	4	30	820
ECT	Maasvlakte	Rail	35	18		218710
CCT	Moerdijk	Rail	20	19	30	45368
RT	Eindhoven	Rail	35	22	25	0
BRTB	Born	Rail	35	26	25	36
Railterminal	Ede	Rail	35	40	30	6235
RT	Leeuwarden	Rail	35	97	25	5460
RSC	Groningen	Rail	47,5	109	25	85716
CCT	Moerdijk	Barge	65	136	30	38937
ECT	Maasvlakte	Barge	45	141		806293
Zeeland Seaports	Vlissingen	Barge	30	153	30	24303
Bossche Container Terminal	Den Bosch	Barge	20	171	30	104317
Harlingen Seaport	Harlingen	Barge	90	186	45	5713
Multimodal Container Services	Meppel	Barge	81,3	192	20	23559
Multimodal Container Services	Groningen	Barge	225	194	25	42858
Combi Terminal Twente	Hengelo	Barge	45	198	25	91530
Ossche Overslag Centrale	Oss	Rail	35	207	20	721
Ossche Overslag Centrale	Oss	Barge	45	208	35	30390
Barge Terminal	Tilburg	Barge	45	209	20	41693
BRTB	Born	Barge	30	210	25	114199
ROC	Maastricht	Barge	45	211	25	32868
CT Valuepark	Terneuzen	Barge	45	212	15	74453
CT Valuepark	Terneuzen	Rail	35	213	15	0
ECT	Venlo	Barge	46,5	214	20	119184
ECT	Venlo	Rail	21,5	215	20	114407
Ceres	Amsterdam	Barge	44,2	216	10	18021
Ceres	Amsterdam	Rail	35	217	10	4414
RSC	Rotterdam	Rail	35	218	10	93581
ROC	Kampen	Barge	45	219	35	16304
EIT	Wanssum	Barge	17,5	221	30	92252
CT	Utrecht	Barge	45	225	15	34658
CTVrede	Zaandam	Barge	32	226	15	41036
CT	Nijmegen	Barge	31,5	359	15	94653
ECT	Rotterdam	Barge	45	367	10	408118

VI. Production and consumption of containers

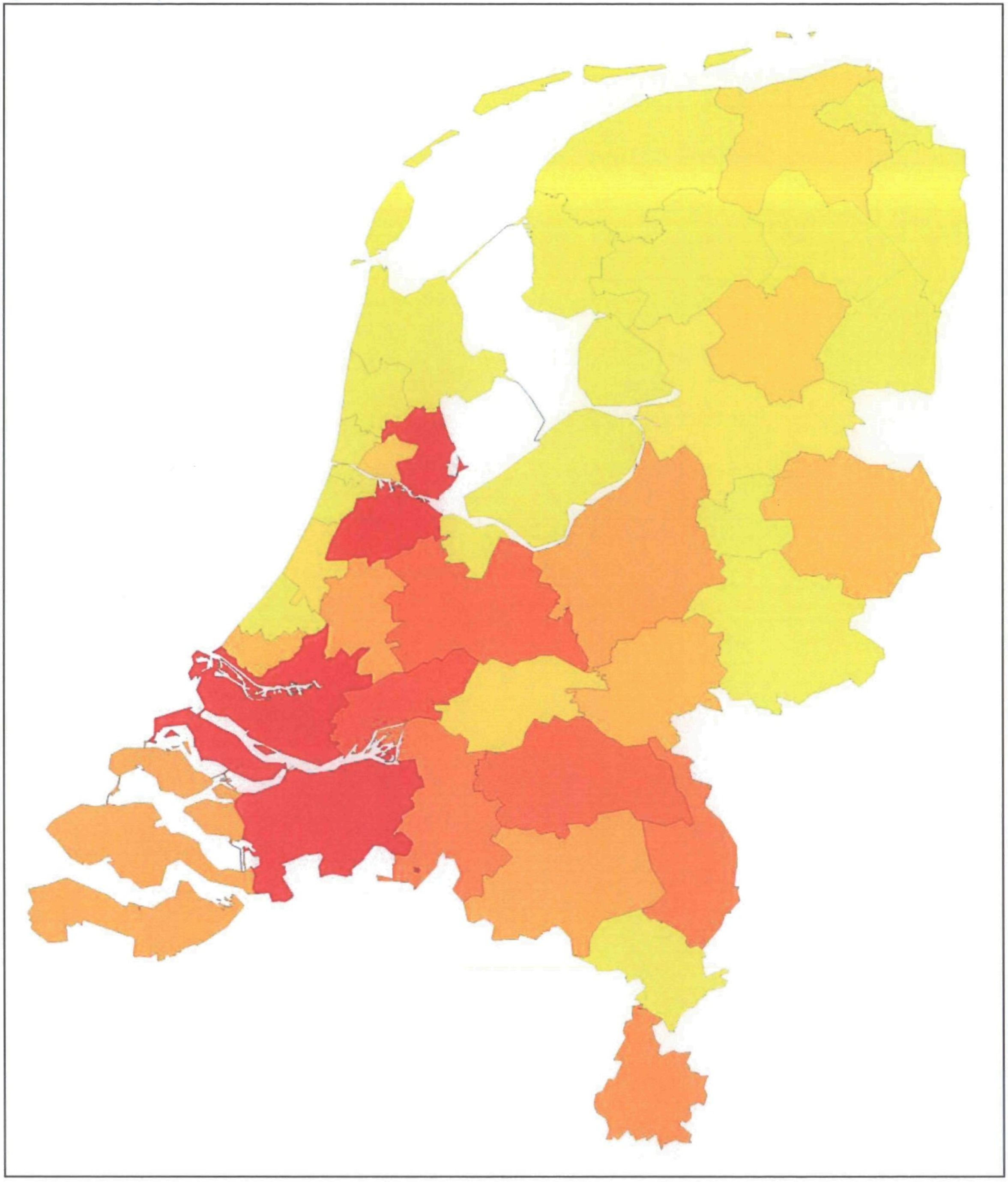
Figure A.1: Production of containers in the Netherlands



Legend:

Colour	Minimum	Colour	Minimum	Colour	Minimum	Colour	Minimum
🟨	0	🟧	50000	🟥	100000	🟥	180000
🟨	12500	🟧	62500	🟥	120000	🟥	200000
🟨	25000	🟧	75000	🟥	140000	🟥	300000
🟧	37500	🟧	87500	🟥	160000	🟥	400000

Figure A.2: Consumption of containers in the Netherlands



Legend:

Colour	Minimum	Colour	Minimum	Colour	Minimum	Colour	Minimum
🟨	0	🟧	50000	🟥	100000	🟥	180000
🟨	12500	🟧	62500	🟥	120000	🟥	200000
🟨	25000	🟧	75000	🟥	140000	🟥	300000
🟧	37500	🟧	87500	🟥	160000	🟥	400000

VII. Required power of inland ships

	Water depth:	Speed (km/h)	6	8	10	12	14	16	18
Class II	a		6	15	28	50	88	155	271
	b		6	15	38	65	130	296	720
	c		7	17	42	74	155	407	1450
Class III	a		11	25	54	85	148	256	439
	b		11	26	63	113	223	489	1115
	c		12	29	71	130	268	651	2163
Class IV	a		14	31	65	104	178	306	523
	b		14	33	78	140	273	598	1369
	c		14	36	88	161	332	803	2728
Class Va	a		24	55	112	179	303	510	860
	b		23	54	127	233	456	988	2195
	c		24	60	145	274	565	1348	NA
Class VIb	a		70	150	290	453	724	1151	1854
	b		70	162	367	672	1267	2678	NA
	c		76	184	434	818	1652	3855	NA

VIII. Normalised income statement of an inland ship

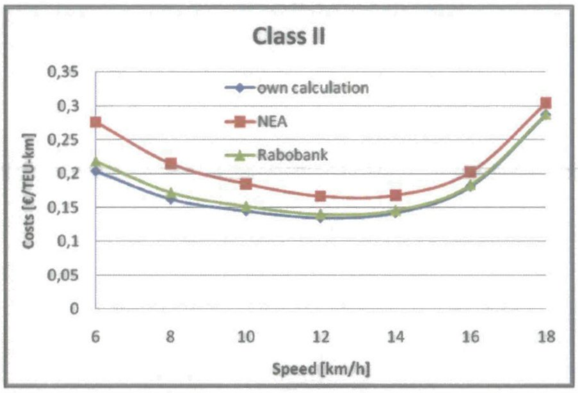
Inland shipping
Income statement (in of the revenue)

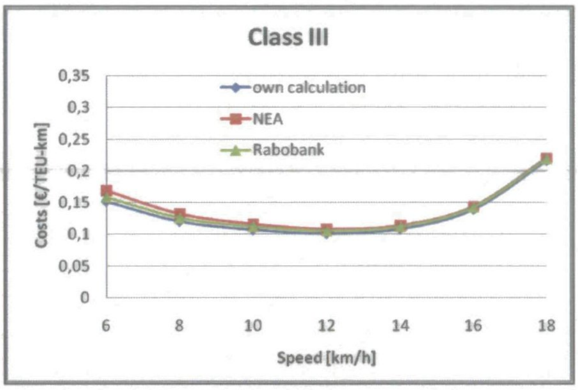
	MKB
	2008
Revenue	100,0
Purchase: fuel and harbour fees	25,9
Third party labour	0,2
Gross profit	73,9
Other income	1,6
Total income	75,5
Total costs	65,9
Labour	17,1
Housing and ship	12,6
Other, administration and communication	8,3
Depreciation	15,4
Financial expenses	12,5
Result before tax	9,6

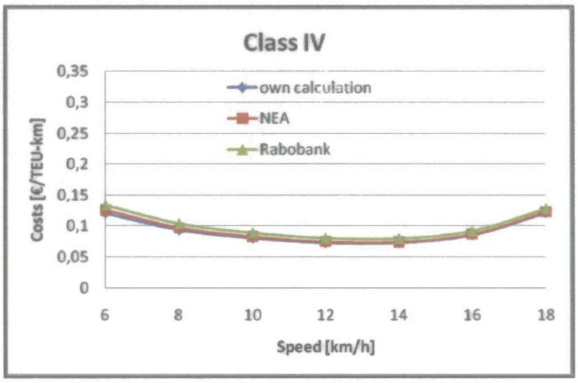
note:
Labour costs are excluding entrepreneurs fee
Ship costs are maintenance, insurance and lubricants

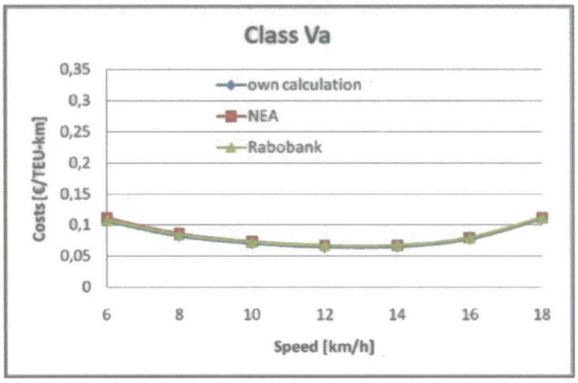
Source: (Rabobank, 2010), translated from Dutch

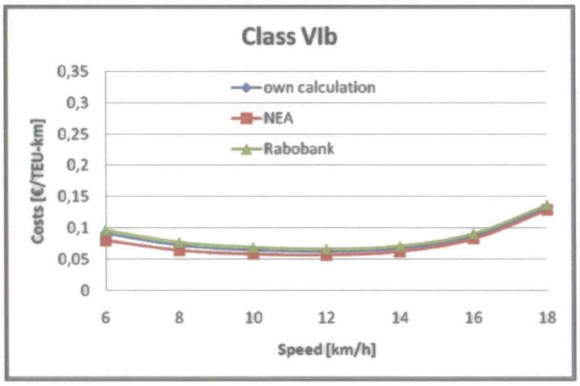
IX. Costs of all ship types











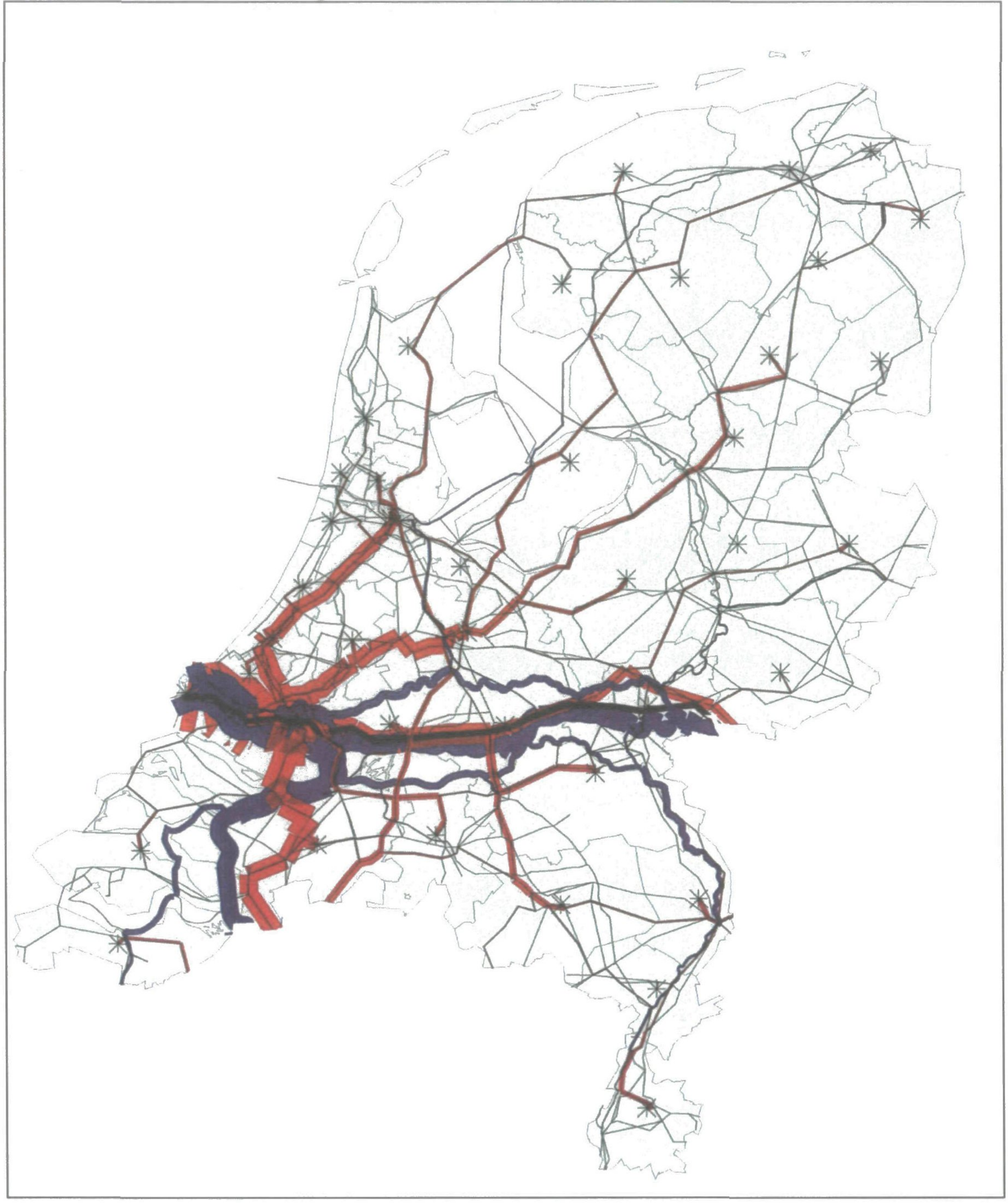
X. Transhipment costs iterations

Terminal	Iteration:	1	2	3	4	5	6	7	8	9	10
19		1	1	1	1	1	1	1	1	1	1
109		1	1	1	1	1	1	1	1	1	1
136		0	0	0	0	1	1	1	1	1	1
153		1	1	1	0	0	0	1	1	1	1
171		0	0	0	1	0	1	1	1	1	1
186		1	1	1	1	1	1	1	1	1	1
192		1	1	1	0	1	1	1	0	1	1
194		0	0	0	0	0	0	0	0	0	0
198		1	1	1	1	1	1	1	1	1	1
210		1	1	1	1	1	1	1	1	1	1
214		1	1	1	1	1	1	1	1	1	1
215		1	1	1	1	1	1	1	1	1	1
216		0	0	1	0	0	1	1	1	0	1
221		1	1	1	1	1	1	1	1	1	1
226		1	1	1	0	0	1	1	1	1	1
359		0	1	1	1	1	1	1	1	1	1
	Average	1,261	1,155	1,147	1,310	1,240	1,201	1,078	1,067	1,067	1,067
	stdev	0,658	0,520	0,459	0,474	0,404	0,381	0,316	0,286	0,267	0,266

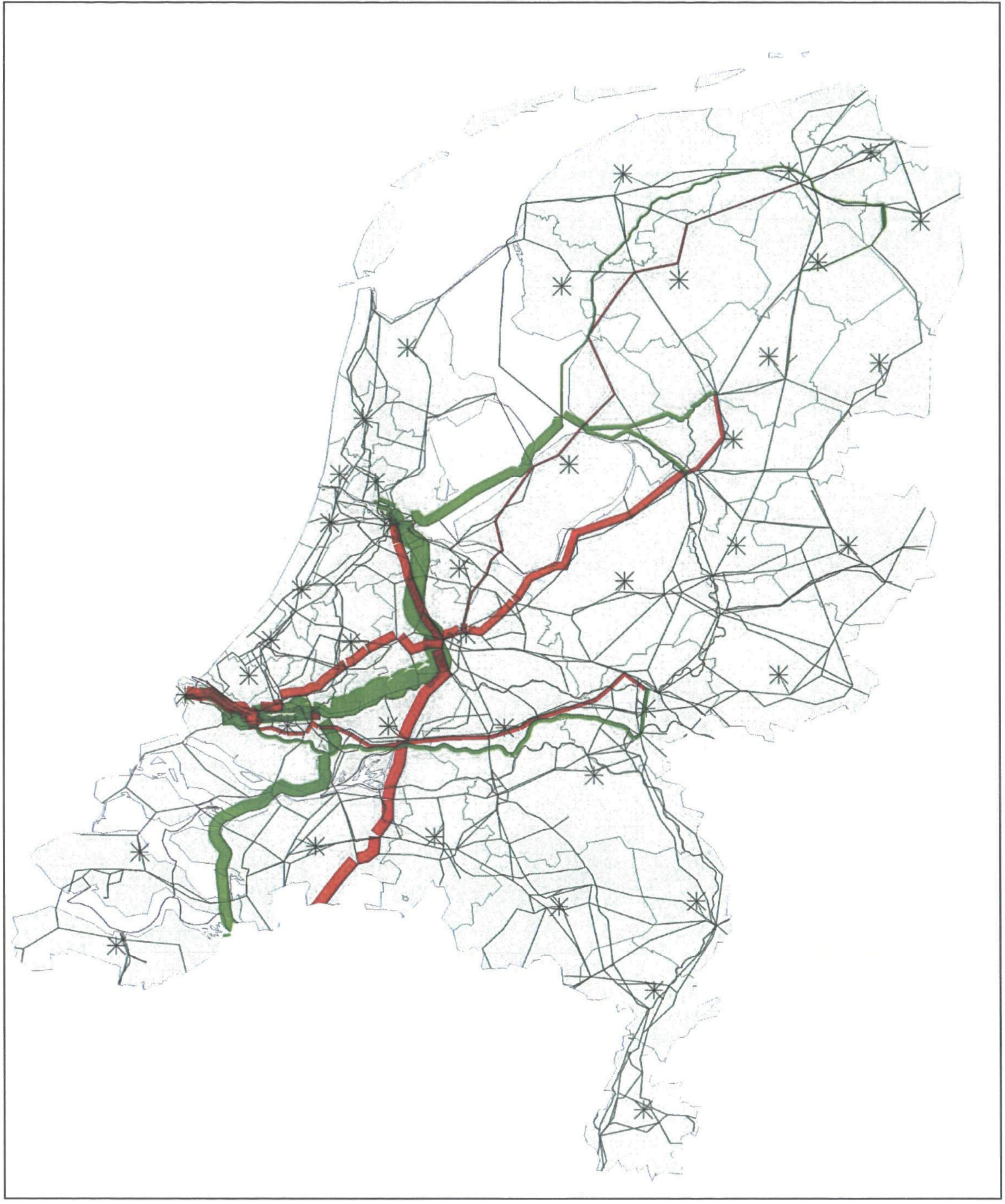
A 1 means that the transhipment numbers of the terminal are within a standard deviation of the average, a 0 means it is not. The next table shows the transhipment costs of the terminals for the same iterations.

	1	2	3	4	5	6	7	8	9	10
19	20,00	20,00	20,00	20,00	20,00	20,00	20,00	20,00	20,00	20,00
109	52,50	47,50	47,50	47,50	47,50	47,50	47,50	47,50	47,50	47,50
136	50,00	52,50	55,00	60,00	65,00	65,00	65,00	65,00	65,00	65,00
153	30,00	30,00	30,00	30,00	30,00	30,00	30,00	30,00	30,00	30,00
171	27,50	22,50	17,50	12,50	15,00	16,25	17,50	20,00	20,00	20,00
186	90,00	90,00	90,00	90,00	90,00	90,00	90,00	90,00	90,00	90,00
192	87,50	85,00	82,50	77,50	80,00	81,25	82,50	82,50	81,25	81,25
194	129,17	150,00	150,00	150,00	150,00	150,00	150,00	175,00	200,00	225,00
198	45,00	45,00	45,00	45,00	45,00	45,00	45,00	45,00	45,00	45,00
210	30,00	30,00	30,00	30,00	30,00	30,00	30,00	30,00	30,00	30,00
214	37,50	37,50	38,75	41,25	45,00	46,25	46,25	46,25	46,25	46,25
215	12,50	12,50	13,75	16,25	20,00	21,25	21,25	21,25	21,25	21,25
216	52,50	50,00	47,50	45,00	45,00	43,33	43,33	45,00	45,00	44,17
221	20,00	18,75	17,50	17,50	17,50	17,50	17,50	17,50	17,50	17,50
226	34,50	33,33	32,08	32,08	32,08	32,08	32,08	32,08	32,08	32,08
359	40,00	35,00	32,50	28,75	28,75	30,00	31,25	31,25	31,25	31,25

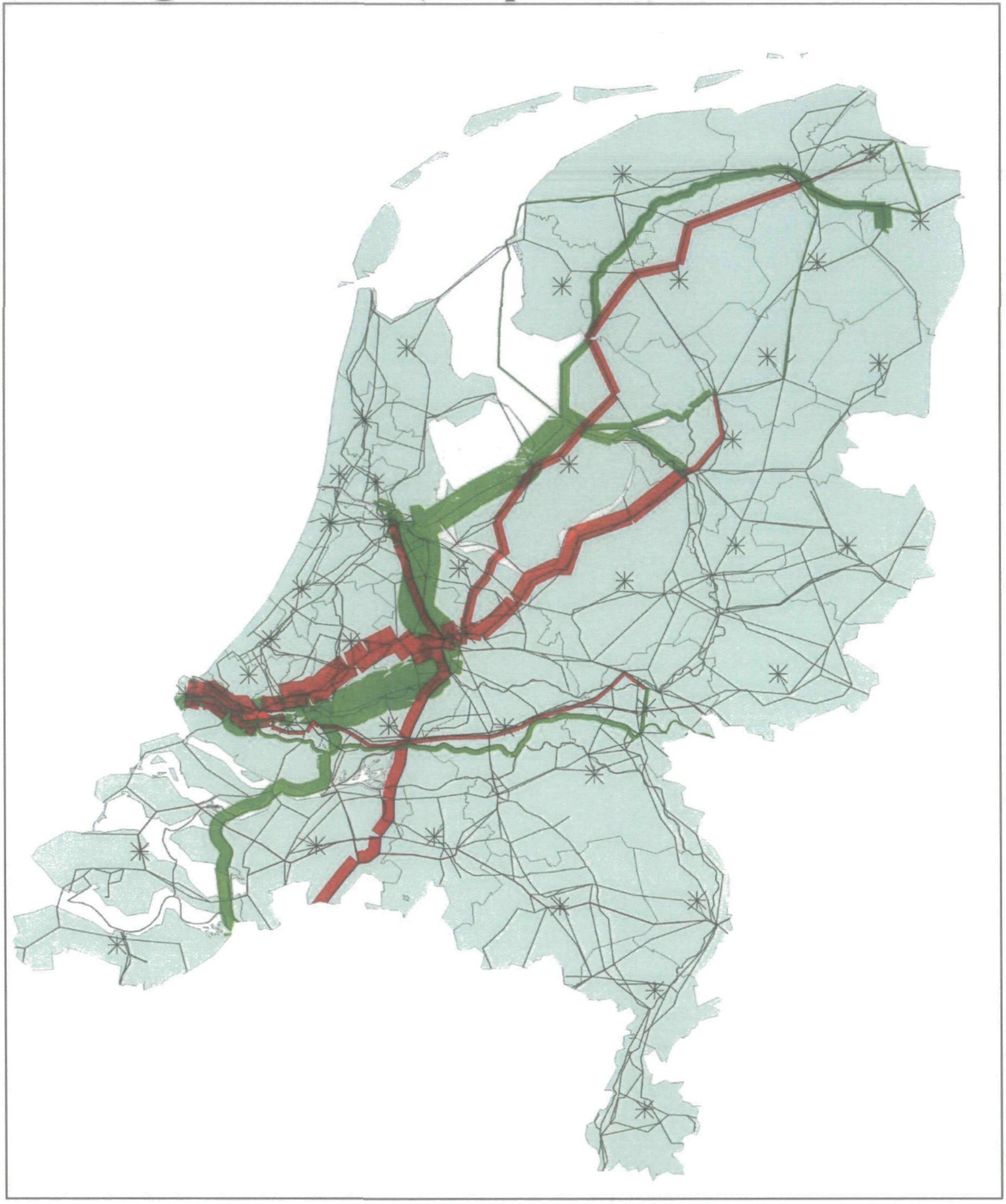
XI. Container transport in the reference scenario



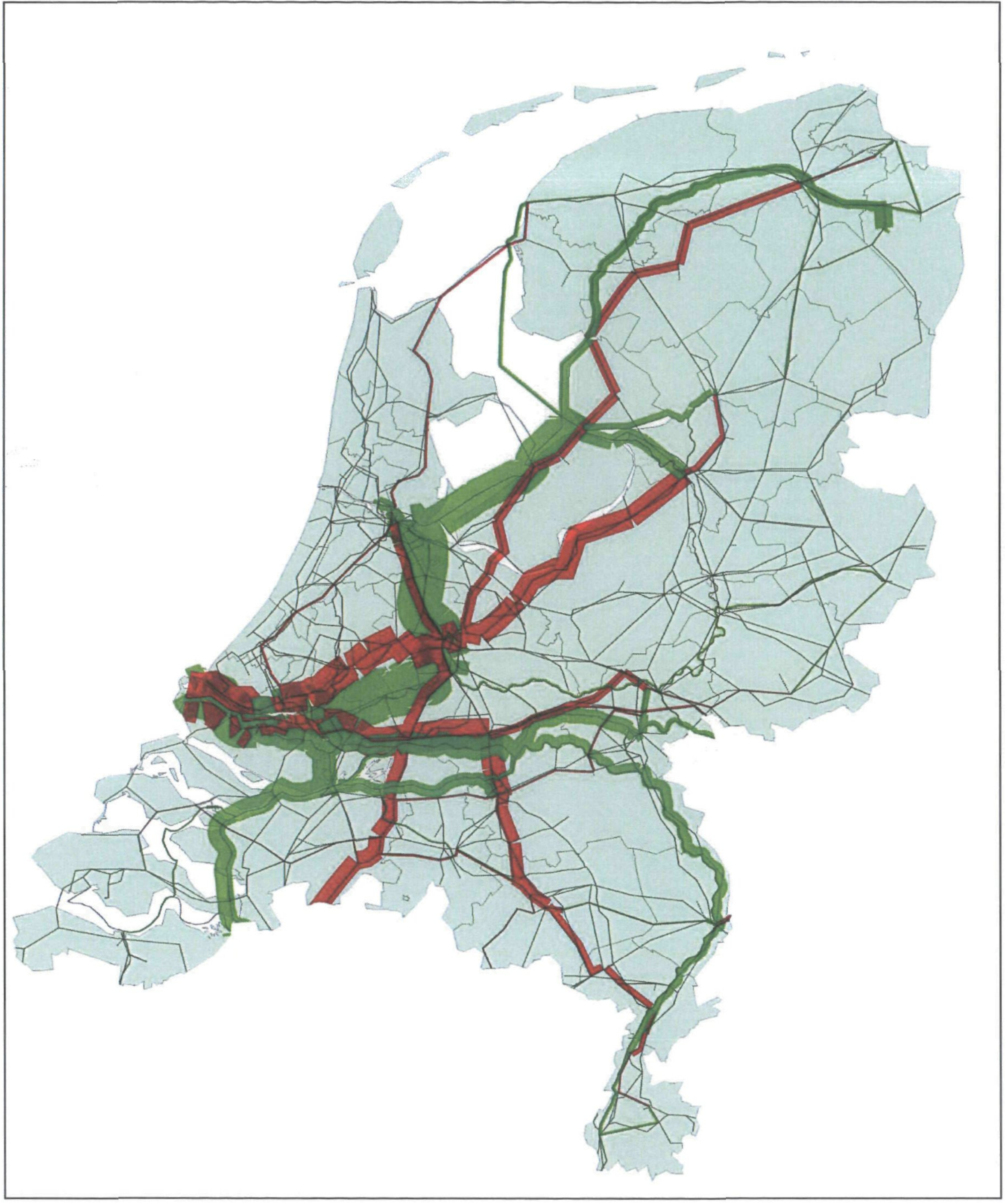
XII. Change in network use, CO_2 price €10/ton



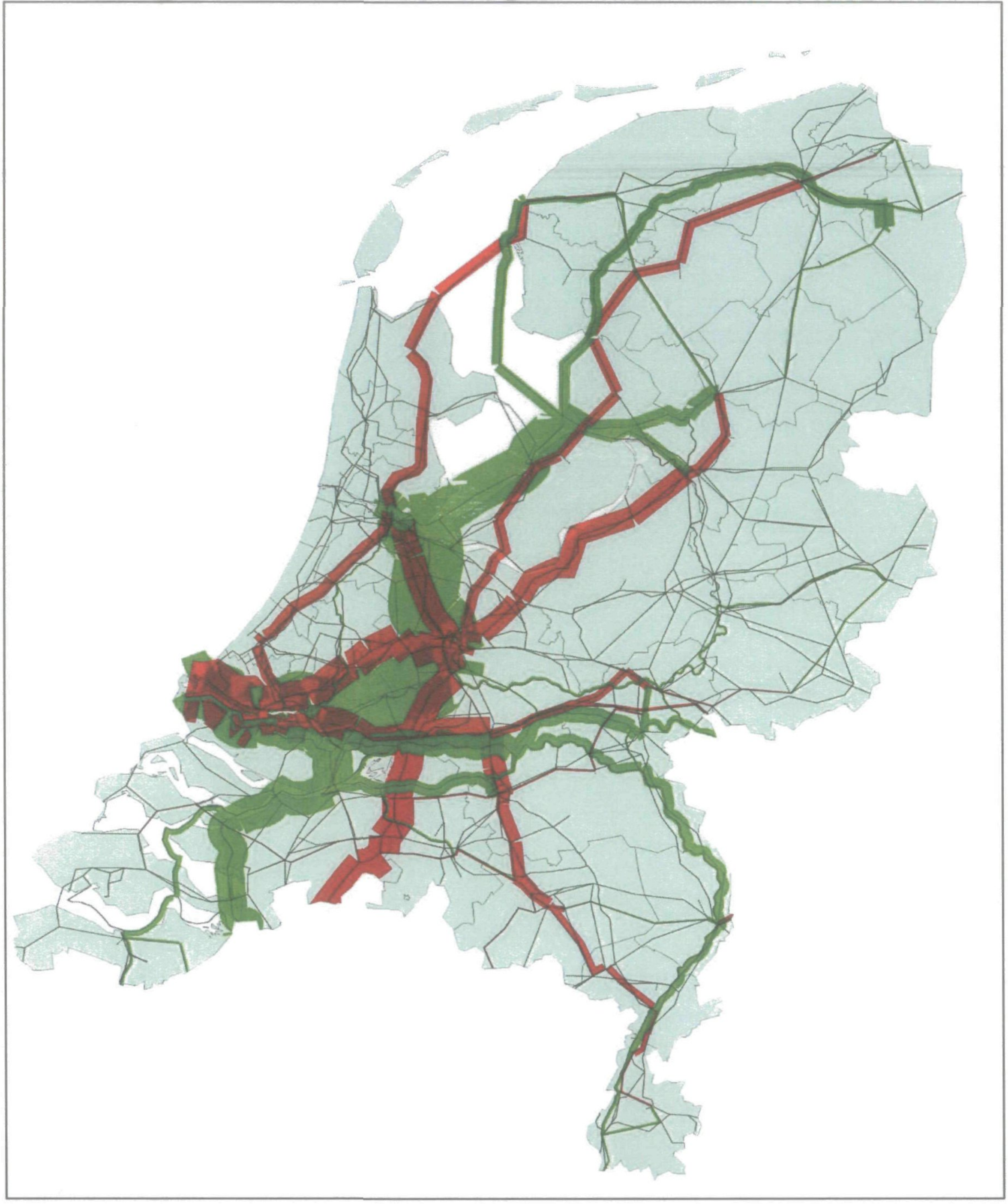
XIII. Change in network use, CO_2 price €40/ton



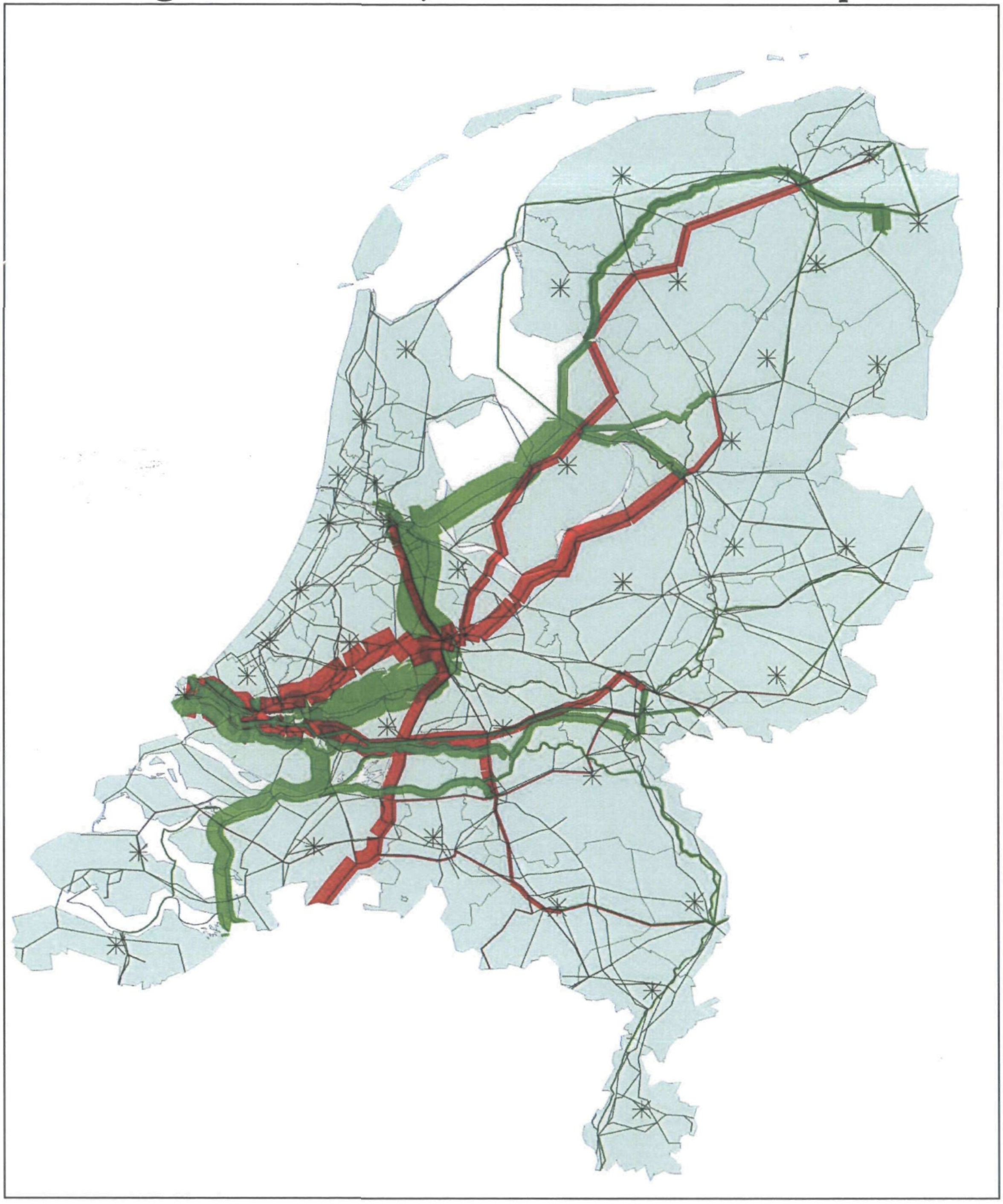
XIV. Change in network use, CO_2 price €100/ton



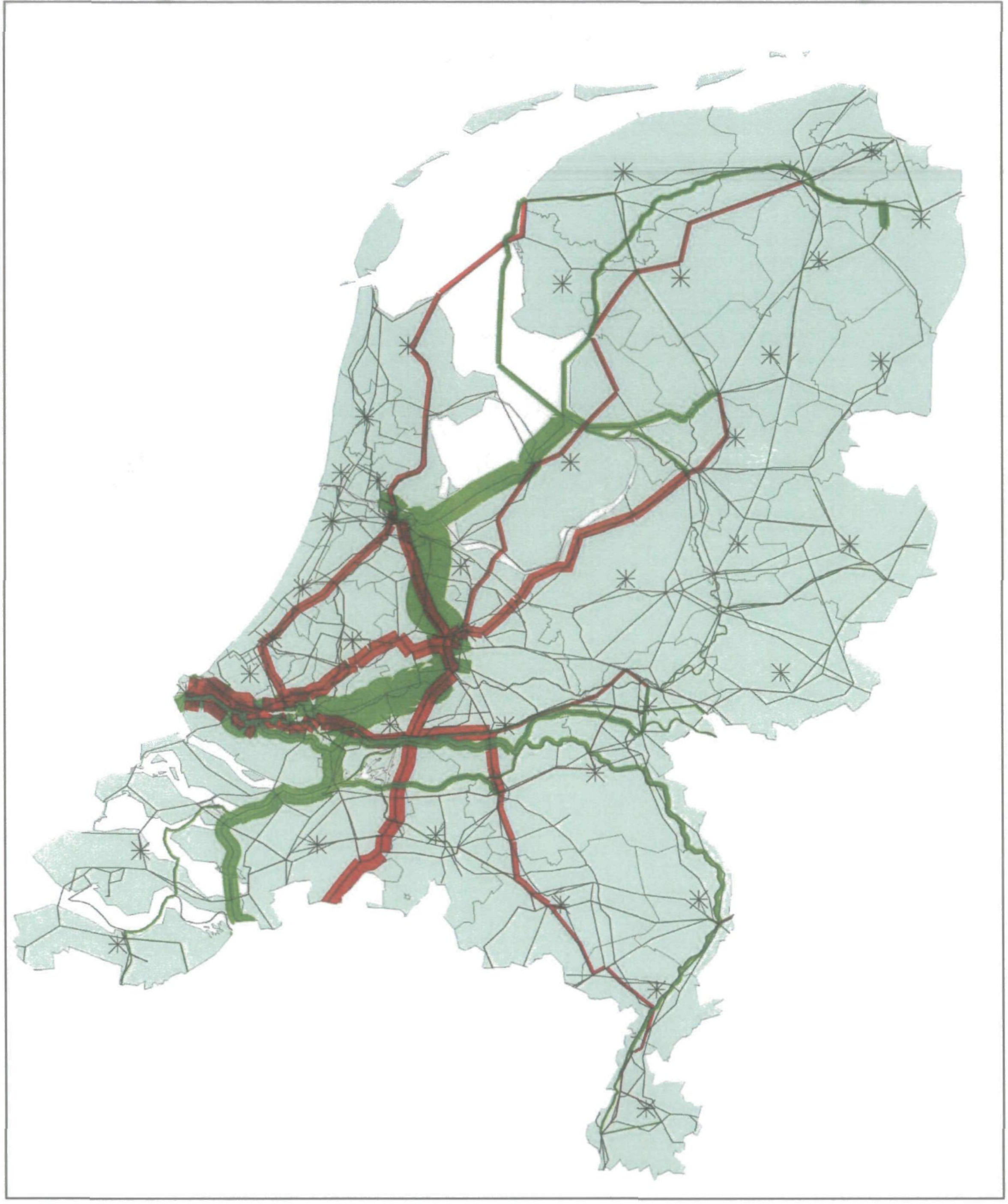
XV. Change in network use, CO$_2$ price €150/ton



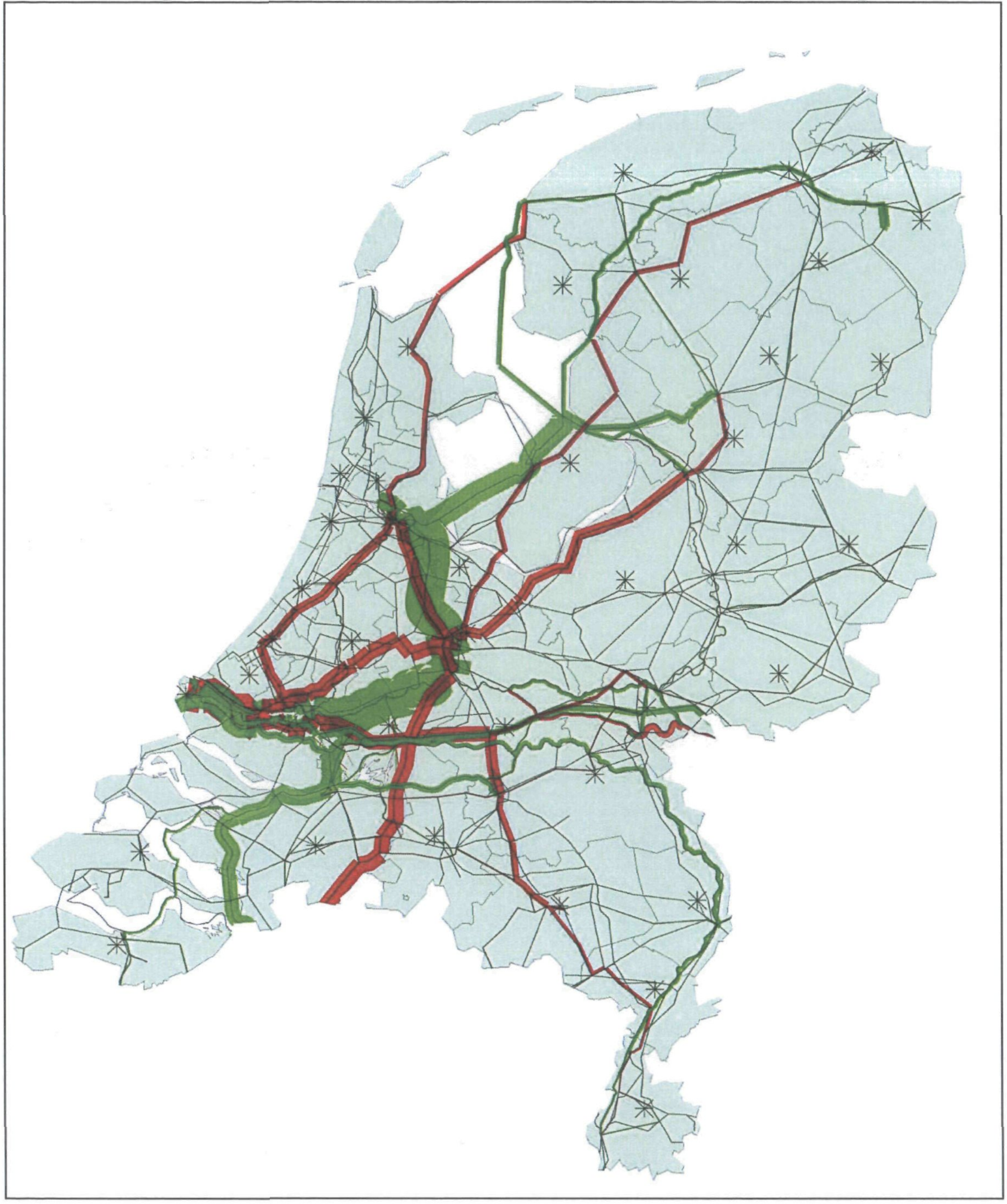
XVI. Change in network use, B30 biodiesel in road transport



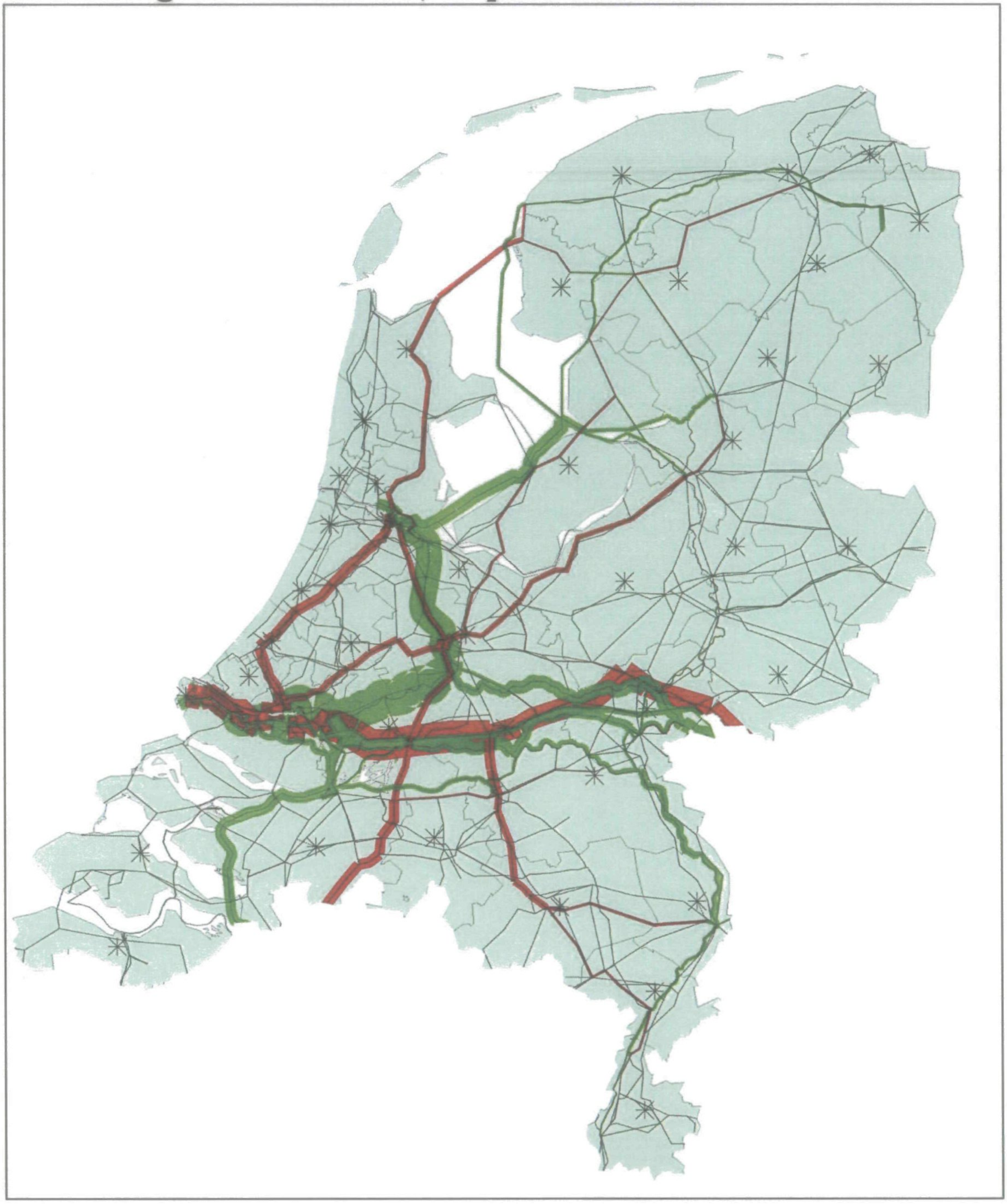
XVII. Change in network use, B100 biodiesel in road transport



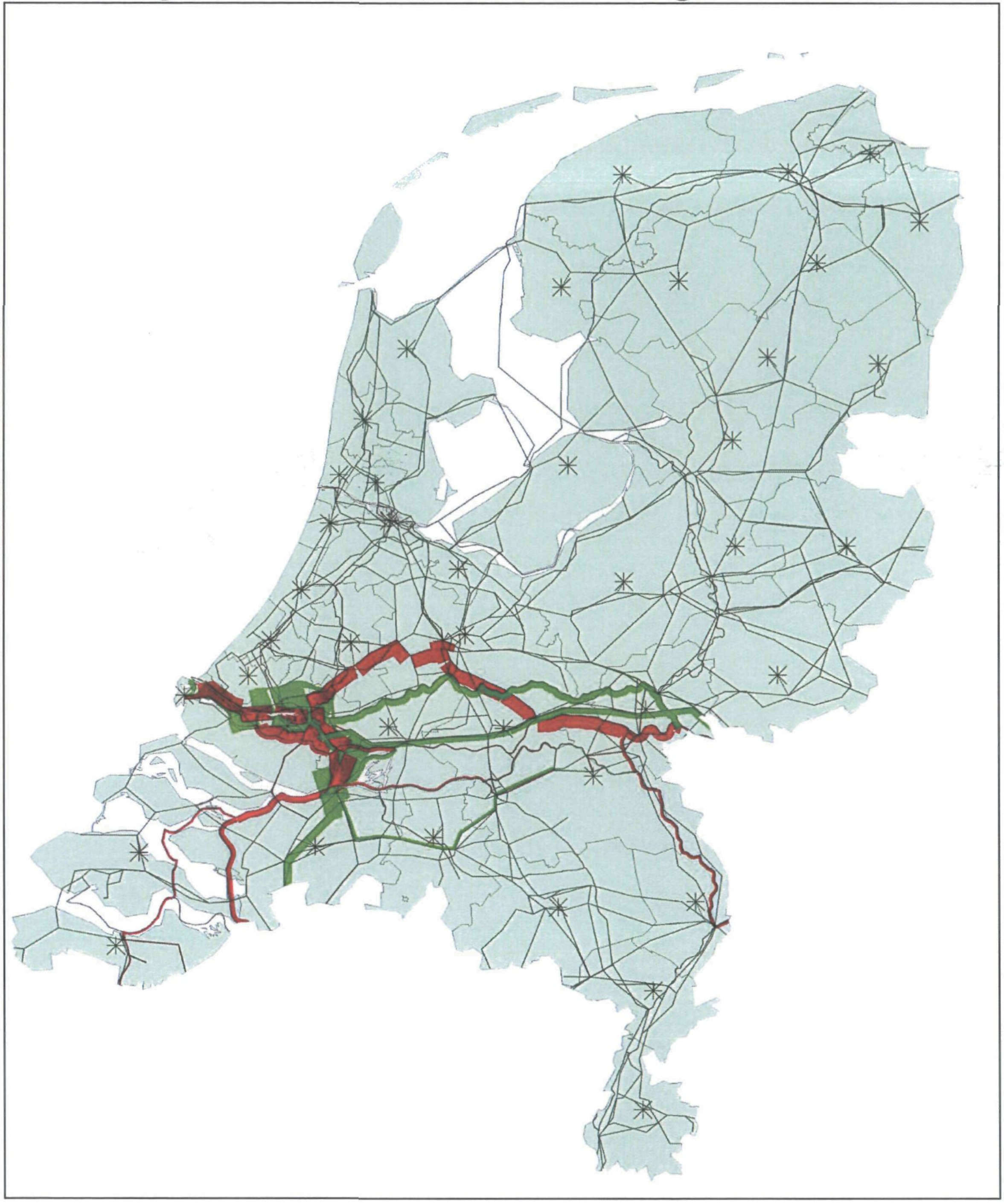
XVIII. Change in network use, B100 in road and IWW transport



XIX. Change in network use, oil price times two



XX. Change in network use, 1 additional barge terminal



XXI. Change in network use, 1 additional rail terminal