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# Changes in external costs and infrastructure costs due to modal shift in freight transport in North-western Europe

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## Abstract

Modal shift in freight transport entails moving freight from road to rail, inland waterways, and short sea shipping. In current Dutch and European freight transport policy, modal shift is foreseen to play an important role to mitigate external effects of freight transport. Policy efforts on modal shift are legitimate because the size of the external costs of freight transport are considerable. But can modal shift policies also be effective? In other words, can policy efforts on modal shift result in a decrease of external costs and infrastructure costs due to freight transport? Our research approach falls apart into three steps. In the first step we analyse the transported weight by road on four international freight corridors in North-western Europe that could be transported against at least 10% lower private costs by rail or inland waterways. The share of road transport (transported weight) on the corridors in total road transport in the Netherlands is about 10%. The weight of the cargo that could potentially be shifted on the basis of the transport cost criterium is called the modal shift potential (MSP). We estimate the MSP for the base year 2018 and for the future year 2050. Also in this step, we translate the MSP into changes in transport performance per transport mode. In the second step we determine differences in external costs and user dependent infrastructure costs per unit of transport performance (tonkm) between the transport modes road, rail, and inland waterways. The following external effects are included: greenhouse gas emissions (tank-to-wheel), air pollutant emissions (tank-to-wheel), noise, traffic accidents, congestion, and emissions from fuel and electricity production (well-to-tank) for freight vehicles. Including all these effects, we take a more integral approach than existing studies on the effect of modal shift on the external costs of freight transport. In the third step, we combine the results of steps 1 and 2 and calculate the changes in external costs and infrastructure costs that result from the MSP's. We find MSP's of between 35 and 55%, depending on the market segment (container, or non-container transport, and year). These percentages may seem substantial, but we emphasize that on the freight transport corridors rail and inland waterways are (very) competitive to road. Estimates for the decrease in external- and user dependent infrastructure costs if the MSP's are fully realized point to reductions of €67 million to €150 million for the Netherlands, and €87 million to €136 million abroad for 2018 (considering all countries through which the corridors pass). We emphasize that these are maximum annual savings which can only be

achieved if all non-transport cost obstacles for modal shift can be removed. For 2050 estimating a maximum and minimum for the change in external- and infrastructure costs is impossible due to uncertainties in the development of the transport costs and the external costs of freight transport. Because for the year 2018 the MSP's result in a decrease of external costs and infrastructure costs from freight transport on the corridors, we conclude that in the coming years policy efforts on modal shift can be effective. We can however not conclude anything about the efficiency: are the benefits of policy efforts on modal shift larger than the costs? If that is not the case, taking modal shift measures can eventually not be justified from an economic welfare point of view.

**Keywords:** Modal shift, Modal shift potential, Freight transport, External costs, Infrastructure costs

## Introduction

This research is about external costs and infrastructure costs for the government due to freight transport and to what extent modal shift can mute these costs. Modal shift in this study pertains to the movement of cargo flows from road to rail and inland waterway transport. External costs are the result of external effects. External effects occur when effects of economic activities of one actor on the welfare level of another actor are not taken into account in the prices of the goods or services provided (Boneschansker en 't Hoen 1992). We define infrastructure costs for the government as the infrastructure costs after deduction of infrastructure charges and taxes that accrue to the government.

### Policy background

In the past decades in the European Union and in the Netherlands several programme's for the stimulation of modal shift in freight transport have been set up. See for example the Marco Polo programmes I and II (European Union 2020) and the Dutch Freight Transport Agenda (Min. IenW 2019). Relieving congestion on road networks and reducing emissions of the freight transport system as a whole are arguments that are raised by policy makers to justify measures that stimulate modal shift.

We investigate whether (1) a modal shift from road to rail or inland waterways on four international freight transport corridors through the Netherlands can be achieved and (2) if such a shift indeed results in lower external costs and lower infrastructure costs for the government.

### Research goal and research questions

The main goal of our research is to determine if policy efforts on modal shift can be effective, now and in the future. That is the case when the external costs and the infrastructure costs for the government of freight transport can decrease as a result of those policy efforts.

Effectiveness is not the only criterium to look at in order to judge if policy efforts on modal shift can be justified. The other criteria are legitimacy and efficiency.

Legitimacy is the first criterium to consider and is about whether or not there is a reason for government intervention in a market. The negative external effects, with corresponding costs, from freight transport can be brought forward as a valid reason. CE

Delft (2022a) have calculated that total external costs generated by trucks, freight trains and inland waterway vessels sum up to about €4 billion per year for the Netherlands. Policy efforts are therefore legitimate. The second criterium is effectiveness, on which we focus in this research. Modal shift measures are effective if they lower the external costs and the infrastructure costs for the government. The third and last criterium is efficiency. Here the question is whether the social benefits of the modal shift measures outweigh the costs of the measures. The potential decrease of the external costs and the infrastructure costs for the government is a benefit, as is the possible drop in transport costs for transport companies.

In order to answer the main question ("Can policy effort on modal shift be effective"?), we answer the following three research questions:

1. In which segments of the freight transport market in North-western Europe is a modal shift possible, now and in the future (2050), and what is the potential magnitude of those shifts?
2. How big are the differences in external costs and in infrastructure costs for the government per transport performance (tonkm) between the transport modes in those segments, now and in the future (2050)?
3. What is the annual potential decrease of external costs and infrastructure costs for the government associated with the shifts calculated in research step 1, now and in the future (2050)?

### Scope

We delineate our research on the following dimensions:

- Cargo segments: we distinguish between the 'container' and the 'non-container' segments. The non-container segment comprises dry bulk, liquid bulk and general cargo.
- External effects: we include the costs of the external effects (1) traffic accidents, (2) air pollutant emissions (tank-to-wheel), (3) greenhouse gas emissions (tank-to-wheel), (4) noise, (5) congestion, and (6) greenhouse gas emissions and air pollutant emissions from fuel and electricity production for vehicles (well-to-tank emissions).
- Years: we perform analyses for the years 2018 and 2050. We choose 2050 as a future year because it is an important year for climate goals (Klimaatakkoord 2019; EC 2019) and one of our analyses considers a situation in which freight transport has become more sustainable in terms of emissions.
- Uncertainty: we face several uncertainties. Firstly, the figures for the unit external cost and infrastructure costs of CE Delft (2022a, b, 2019a, b, c) involve uncertainty in the data used, the valuation methods used, and the assumptions made for drawing up these figures. We address this uncertainty by working with a bandwidth. Secondly, there is uncertainty regarding the development of the economy and demographics, and thus the volume of freight transport in 2050. We work with a High and a Low scenario to deal with this uncertainty. Thirdly, the development of future

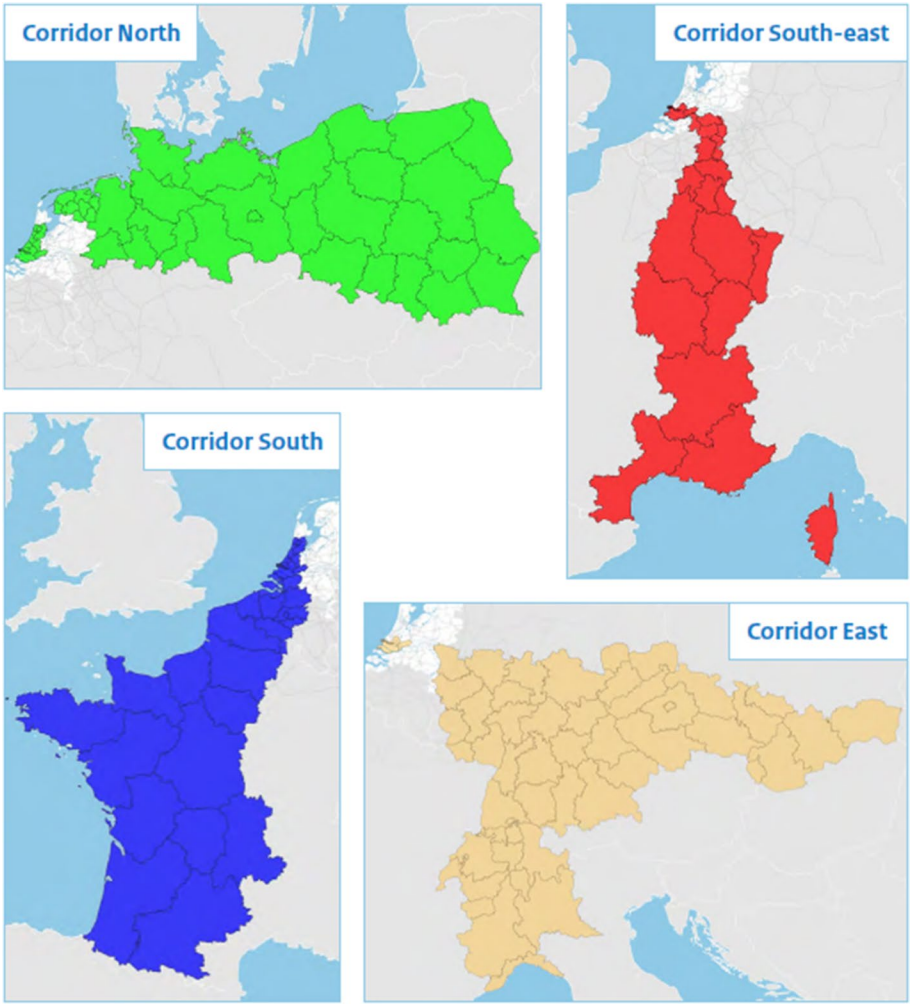


**Fig. 1** The four freight corridors in North-western Europe

freight transport policies and innovation in the freight transport market is uncertain. We take this type of uncertainty into account by performing sensitivity analyses.

- Spatial: this study applies to four international freight transport corridors in North-western Europe. Figure 1 presents the corridors. They are named 'North' (green), 'East' (Yellow), 'Southeast' (red), and 'South' (purple). The selection criteria for the geographical scope is:
- On which routes (connections) do we observe relatively large freight flows by road
- Which regions are served by these flows
- Is rail or inland waterways an attractive alternative in terms of the availability of infrastructure for these modes.

Because of these characteristics modal shift is relatively promising on the corridors. Using the criteria 1–3 our definition of a corridor comes close to the definition of ITF (2022, p. 66): "In a corridor, all modes of transport follow the same spatial orientation

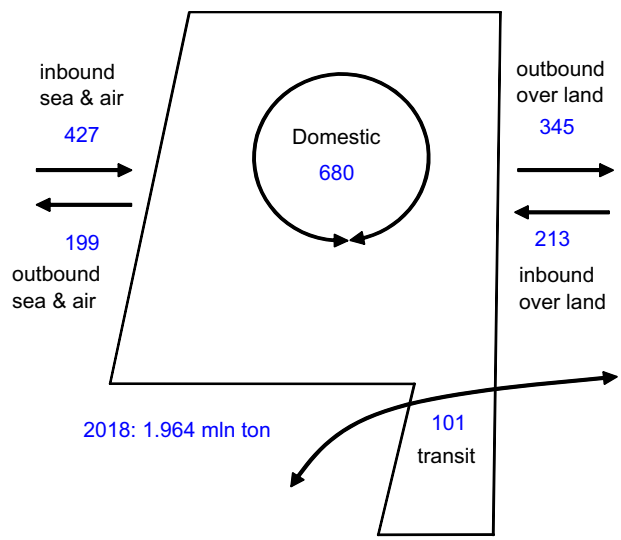


**Fig. 2** Transported weight (tons) in the Netherlands 2018 (*Source*: KiM 2019)

and serve the most important agglomerations and economic centres within their route". All road freight transport on our corridors with an origin or destination in the sea port regions of Rotterdam and Amsterdam and their surroundings regions is included in our study, except for some Dutch regions on the corridor East. Those regions are small origins or destinations in terms of the amount of freight. Origins and destinations are defined at the NUTS level. Appendix A provides tables with the names of the included NUTS regions per corridor.

### Freight transport in the Netherlands

As explained we focus our analysis on international freight corridors through the Netherlands. In order to value the results of our research it may be helpful to have an understanding of the broader spatial context of freight transport in the Netherlands though.

In Fig. 2 we present the picture for 2018 because it is the base year for our analysis. With 65%, the majority of freight transport in the Netherlands is border crossing. Focusing on inbound and outbound transport over land (road, rail, inland waterways, and pipeline), the share is 28%. Freight transport on the corridors takes place within this segment.

Figure 3 applies to all freight transport on Dutch territory and shows that road transport has the largest share in the modal split based on transport performance (tonkm) and rail is smallest. In 2018 the modal split was 47% for road, 36% for inland waterways, 12% for pipeline, and 5% for rail.

### Research steps

In Fig. 4 we present the research steps which we perform in order to answer the research questions 1–3.

First, we determine for the international freight transport corridors to what extent cargo transported by road can be transported by rail and inland waterways at, at least 10% lower private costs. We have used a mode choice model and a transport cost model

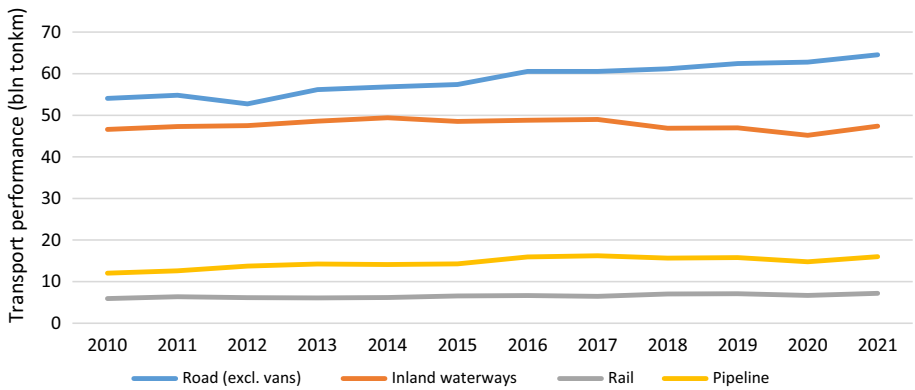


**Fig. 3** Development of transport performance on Dutch territory of land based transport modes between 2010 and 2021 in billion tonkm. *Source*: KiM (2022)

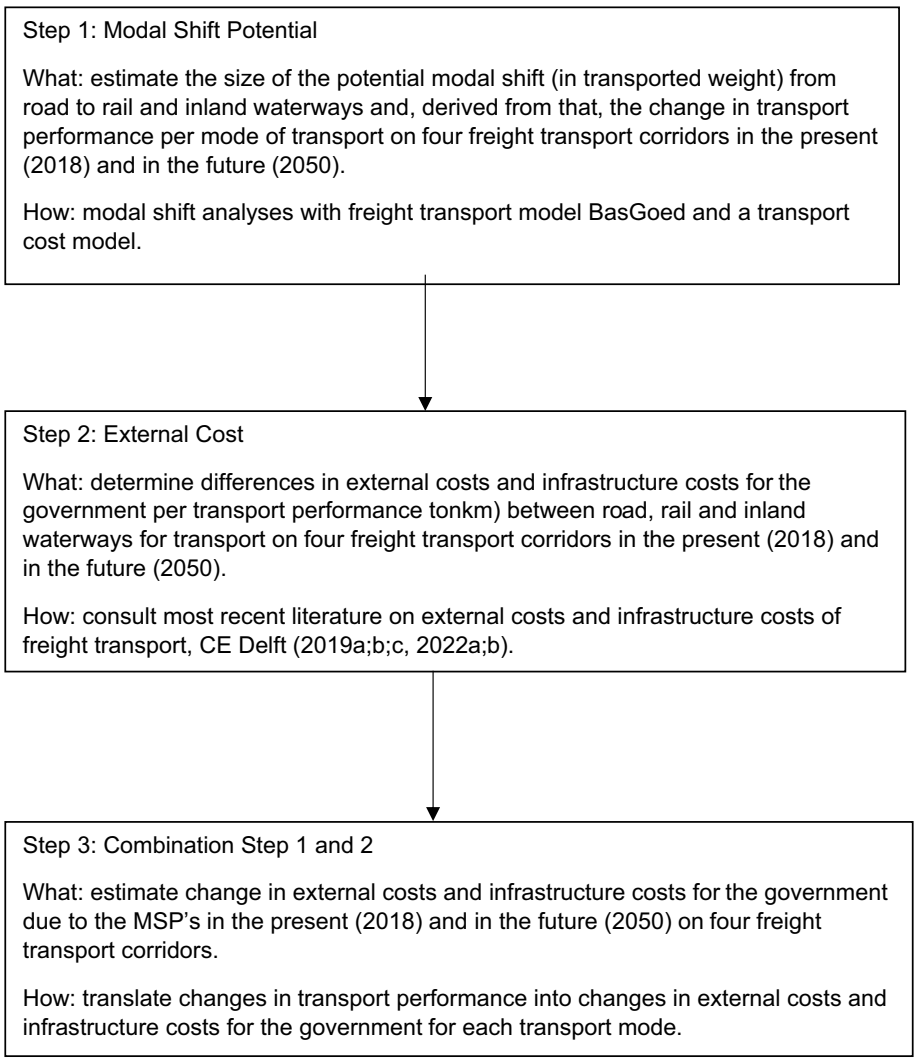


**Fig. 4** Research steps

to determine the potential magnitude of those shifts (in ton). The modal shifts imply changes in transport performance (tonkm) of each transport mode.

Next we determine to what extent the external costs and infrastructure costs for the government per transport performance (tonkm) for road transport, rail transport and inland waterway transport differ from each other. We do this on the basis of figures for the unit costs of external effects and of the use of infrastructure from CE Delft (2019a, b, c, 2022a, b) and the spreadsheets associated with those publications.

Finally, we combine the information obtained in step 1 and step 2. So we calculate the change in the external costs and infrastructure costs for the government on the freight transport corridors by multiplying the changes in transport performance of each transport mode with the relevant figures on unit external- and infrastructure costs and charges.

### Structure of the paper

Our paper is structured as follows. "Literature" section discusses the available literature regarding the potential size of modal shift on freight corridors and changes in external costs and infrastructure costs due to modal shift. "Methodology" section describes the methodology: the data and models used. "Results" section presents the results belonging to the three research steps in Fig. 4. In "Conclusion" section, the conclusion, we answer the research questions, we provides some focus points for policy makers, and we do some recommendations for further research.

## Literature

In this section we position the current paper in the existing literature on (1) the potential size of modal shift on several freight transport corridors and (2) the effect of modal shift on the external costs and infrastructure costs of freight transport. We have obtained the relevant literature with Google Scholar using search words like 'modal shift (potential)', 'freight transport corridors', 'Europe', and 'external costs'. In addition, we have collected studies on modal shift which have been carried out by consultants by order of the Dutch Ministry of Infrastructure and Water Management.

### Potential size of modal shift

In the studies discussed in this section the potential size of modal shift is named 'Modal Shift Potential' (MSP) and is determined as the (share of the) transported weight by road that could have been transported at lower costs by rail or inland waterways. Table 1 presents the main aspects of the studies.

Panteia (2016) estimates the MSP of continental cargo flows by road on the East and Southeast corridors (see Fig. 1) for 2014. Their focus is on container transport only. They find that 48% of the transported weight by road on the two corridors can be shifted to rail or inland shipping. If possibilities for cargo bundling and the capacity of rail services are taken into account the MSP drops to 27%. The distribution of this share over rail and inland waterways is approximately 50–50 (Panteia 2016, p.69). In 2019, Panteia presented a follow-up study (Panteia 2019), in which they analyse the MSP in other, specific freight transport segments (see Table 1). Those MSP's are expressed in TEUs however, not in a percentage or in transported weight. The same applies to Panteia (2020a), in

**Table 1** Overview of studies about modal shift potential (MSP)

| Modal shift study | Country, region, corridor | Scope | Transport modes | Size MSP |
|---|---|---|---|---|
| Panteia (2016) | Corridors East and South-east (Rotterdam—Germany) | Only continental cargo which can be put in containers<br>Year: 2014 | From road to rail and inland waterways | 48% (of transported weight) from transport cost perspective only<br>27% when options for cargo bundling and capacity of rail services are taken into account |
| Panteia (2019) | Corridors East and South-east (Rotterdam—Germany) | Containers and bulk cargo<br>National and international, maritime and continental cargo flows | From road to inland waterways | Segment national, maritime, containers: 437.000 TEU<br>Segment national, continental, bulk: 372.000 TEU |
| Panteia (2020a) | Corridor South (Amsterdam—Rotterdam—Belgium—France) | Containers and fossile fuels | From road to rail and inland waterways | 360.000 TEU to rail, 1.140.000 TEU to inland waterways |
| TNO (2017) | Several corridors in Netherlands, specific attention for the freight railway 'Betuweroute' | Only containers and break bulk<br>Year: 2014 | From road to rail | Whole Netherlands: in areas with 'overlap' between road and rail: 20% (of transported weight) for containers, 30% for break bulk. 2,8 mln ton can shift to 'Betuweroute' |
| Van de Lande et al. (2018) | Netherlands | Maritime containers | From road to rail and inland waterways | 10–20% |
| Visser et al. (2012) | Netherlands | International road transport by Dutch road freight companies, non-containerized cargo, over more than 300 km | From road to rail and inland waterways | 40% of transported weight in segment mentioned in column 'Scope' could shift to rail or inland waterways in 2009 |
| Zhou et al. (2017) | United States | Year: 2040<br>Distance: > 300 miles<br>Shipment size: > 10.000 tons | From road to rail | 4,1% of road freight ton-miles can be shifted to rail |
| Kurtuluş and Çetin, (2020) | Turkey, corridor Denizli region—Izmir seaports | Containers | From road to rail | Doubling train frequency and reducing the train transit time by 50% is the most effective modal shift policy: the (intermodal) rail share increases from 10,6 to 29,7% |
| Zimmer and Schmied (2008) | European Union | Year: 2006 | From road to rail | 4,5% transported weight by road. 19% when measured in transport performance |
| Havenga and Simpson (2018) | South Africa | Year: 2013 | From road to rail | 15% of transported weight by road. 21% in terms of transport performance |

**Table 1** (continued)

| Modal shift study | Country, region, corridor | Scope | Transport modes | Size MSP |
|---|---|---|---|---|
| Pinchasik et al. (2020) | Norway, Sweden, Denmark | Year: 2030 | Road, rail, sea | Change in transport volume and transport performance compared to reference, depending on (mix of) policy measures taken:<br>Road: [− 0,2%, 0,5%] tons, [− 8,3%, − 0,3%]<br>tonkm<br>Rail: [− 0,1%, 12,2%] tons, [− 0,4%, 47,4%]<br>tonkm<br>Sea: [− 0,8%, 0,2%] tons, [− 0,4%, 0,3%]<br>tonkm |

which only the South corridor was examined. TNO (2017) focuses on areas where cargo flows by road 'overlap' with those by rail. These areas are in fact the freight transport corridors because where there is market overlap, the road and rail infrastructure run more or less parallel to each other. They estimate the MSP (based on transported weight) at about 20% for the container segment and 30% for the general cargo segment. The MSP for the corridor East is 2.8 million tons in 2014. Van de Lande et al. (2018) mention a 10–20% modal shift of maritime containers from road to rail and inland waterways that should be possible in the short term. However, no explanation is provided for this percentage. Visser et al. (2012) report a MSP of 14.9 million tons, which amounts to about 40% for the specific segment of international road transport by Dutch companies of non-containerised cargo over more than 300 km, in 2009.

MSP-research that applies to (freight corridors in) the Netherlands is most relevant for the current study. It is interesting however to also have a look at the potential of modal shift in freight transport in other parts of the world. Zhou et al. (2017) report a 4,1% MSP (measured in ton-miles) from road to rail in the US for shipments larger than 10.000 tons that are transported over 300 miles or more by road by the year 2040. The size of the MSP is determined for each combination of OD-pair and commodity type on the basis of 'technical judgement' (Zhou et al. 2017 p.5). The (difference in) transport costs between road and rail as well as the capacity of the railway network are not taken into account.

Using a stated choice experiment Kurtuş and Çetin (2020) find a 19,1 percentage point decrease in the road share, which shifts to rail for a corridor in Turkey. This shift is the result of taking two policy measures (doubling train frequency and halving train transit time) and applies to container transport (TEU) on the corridor that connects the Denizli region with the Izmir sea ports. Other sets of policy measures result in lower shifts.

Zimmer and Schmied (2008) calculate a theoretical modal shift potential from road to rail for the European Union (the former EU-28 minus Malta and Croatia). They use research results on modal shift potentials per type of goods and per distance class from TRANSCARE and apply these potentials to Eurostat data on types of goods and distances for road transport for all EU-countries. The size of the MSP they find is 4,5% of the volume of goods transported by road and 19% if measured in road transport performance. Also here, differences in transport costs do not play a role in the determination of the MSP.

In a study from South Africa (Havenga and Simpson 2018) the MSP from road to rail is the result of the internalization of externality costs in the transport prices for road and rail. Because transport prices for road increase more than for rail, part of the road freight shifts to rail: 15% of the transported weight by road and 21% of road's transport performance. Interestingly, the macroeconomic freight bill decreases (despite the cost increase due to internalization) due to the returns to density in freight transport.

Last, Pinchasik et al. (2020) analyse the change in transported weight and transport performance for Norwegian commodity flows (domestic and foreign) by road, rail and sea in 2030 in nine policy scenarios. In eight out of nine scenarios the transported weight and transport performance by rail increases. The largest increase is observed in a policy scenario in which longer freight trains are combined with a Norwegian eco-bonus for rail: 12,2% (weight) and 47,4% (performance). Note that the interpretation of

these shares is different from the other shares mentioned in Table 1. They do not apply to shares of road transport that are shifted away to other modes.

Considering all studies in Table 1, the MSP's on freight corridors are larger than the MSP's calculated at the country (or EU) level, as expected. This makes sense because on freight corridors freight flows by road are relatively thick, and transport solutions by rail and inland waterways are at hand. Another observation from Table 1 is that in most studies for the Netherlands inland waterway transport is considered as an alternative for road transport while in studies for other parts of the world only rail is considered.

#### Effect modal shift on external costs of freight transport

In the literature a number of studies that analyse the reduction of external costs and infrastructure costs due to modal shift in freight transport can be found. The size of the modal shift is a given in those studies. Table 2 summarizes the most important aspects of them.

TNO (2017) expresses the reduction in $CO_2$ emissions (and thus in external costs from $CO_2$ emissions) due to modal shift as a share of the original $CO_2$ emissions from road transport before the shift (10%), not as a share of the original $CO_2$ emissions from road and rail together. The percentage will be lower compared to the original $CO_2$ emissions from road and rail together. Rondaij et al. (2020) take a different approach and model a what-if modal shift scenario for container transport on the East and South corridors in 2030. The assumption is that 20% of the transport performance of container road transport over distances of 100 km and more will shift to inland waterways and rail. This results in a 9% reduction in $CO_2$ emissions from container road transport over more than 100 km. Due to the increase in rail and inland waterway transport of containers, the net-decrease in $CO_2$ emissions is 2.8%. The research also shows that the decrease in $CO_2$ emissions due to modal shift is smaller if road transport becomes more sustainable.

Nocera et al. (2018) estimate the reduction of external costs due to a modal shift from road to rail on the Brenner Corridor in Northern Italy for the period 2015–2035. The transported weight on the Brenner corridor in 2015 was approximately 44 million tons. The estimate is based on a modal split (based on transported weight) of 71% road and 29% rail in 2015, shifting to 50–50% in 2027 and ultimately 29% road and 71% rail in 2035. The size of the modal shifts in 2027 and 2035 is based on policy goals. The authors include the costs of five external effects: air pollutant emissions, greenhouse gas emissions, noise, congestion, and traffic accidents. The estimated decrease in external costs amounts to €262 million over the period 2015–2035.

Vierth et al. (2019) evaluate the change in external costs of a modal shift from combined rail-short sea transport to full short sea transport between Stockholm and Hamburg. The motivation behind that evaluation is capacity shortages on the railways in Sweden. The analysis relates to an annual freight transport volume of 120,000 TEU. The costs of the external effects of air pollution, greenhouse gas emissions, noise, congestion, traffic accidents, and water pollution are €3.8 million per year in the case of the combined rail-short sea option, and €5.5 million in the case of the short sea only option (cost level 2010).

Boehm et al. (2021) simulate a modal shift from road to (a hypothetical situation in 2030 of) high-speed rail for high-value goods on the Madrid-Vienna corridor. The

**Table 2** Overview of studies about effect modal shift on external costs of freight transport

| Modal shift study | Country, region, corridor | Types of external effects | Transport modes | Size modal shift | Decrease external costs |
|---|---|---|---|---|---|
| Rondaij et al. (2020) | Netherlands, corridors East and South | GHG-emissions ($CO_2$) | From road to rail and inland waterways | What-if: 20% of tonkm container transport by road over more than 100 km shifts | 2,8% reduction of total $CO_2$-emissions of container transport on corridors East and South in 2030 |
| TNO (2017) | Several corridors in Netherlands, specific attention for the freight railway 'Betuweroute' | GHG-emissions ($CO_2$) | From road to rail | Whole Netherlands: in areas with 'overlap' between road and rail: 20% (of transported weight) for containers, 30% for break bulk. 2,8 mln ton can shift to 'Betuweroute' | Whole Netherlands 2014: decrease $CO_2$ emissions is equal to 10% of emissions of road transport breakbulk + containers |
| Nocera et al. (2018) | Italy, Brenner corridor (both directions) | Air pollutant emissions<br>GHG emission ($CO_2$)<br>Noise<br>Congestion<br>Traffic accidents | From road to rail | 0–30 mln ton per year. Ingrowth 2015–2035 | €262 mln total in period 2015–2035 |
| Vierth et al. (2019) | From Stockholm to Hamburg (one direction) | Air pollutant emissions<br>GHG-emissions ($CO_2$)<br>Noise<br>Capacity restrictions<br>Traffic accidents<br>Water pollution | From rail _ short-sea to short-sea only | 120.000 TEU per year | -€1,7 mln per year, 2010 |
| Boehm et al. (2021) | Corridor Madrid-Vienna (both directions) | GHG-emissions ($CO_2$) | From road to rail | 42% of transported weight from road to high speed rail in 2030 | 79% decrease of $CO_2$ emissions/costs |
| Janic en Vleugel (2012) | Trans-European corridor Netherlands—Greece/Turkey (both directions) | GHG-emissions ($CO_2$)<br>Noise<br>Congestion<br>Traffic accidents | From road to rail | 1559 trucks per week shift to 63 trains per week | 30% decrease of external costs |
| Pinchasik et al. (2020) | Norway, Sweden, Denmark | GHG-emissions ($CO_2$)<br>Air pollutant emissions | Road, rail, sea | Change in transport volume and transport performance compared to reference 2030, depending on (mix of) policy measures taken:<br>Road: [− 0,2%, 0,5%] tons, [− 8,3%, − 0,3%] tonkm<br>Rail: [− 0,1%, 12,2%] tons, [− 0,4%, 47,4%] tonkm<br>Sea: [− 0,8%, 0,2%] tons, [− 0,4%, 0,3%] tonkm | Change in emissions compared to reference depending on (mix of) policy measures:<br>$CO_{2,eq}$: [− 3,6%, 0,1%]<br>$NO_x$: [− 1,1%, 0,3%]<br>PM: [− 0,9%, 0,4%] |

simulation results show that 42% of the transported weight can shift, resulting in a reduction of $CO_2$ emissions and costs by 79%. The relative decrease in $CO_2$ emissions is larger than the share that shifts. A likely explanation is that mostly cargo transported over long distances shifts on this corridor, while cargo transported over short distances remains on the road.

Janic and Vleugel (2012) study the effect of a modal shift from road to rail on the Trans-European Corridor between the Netherlands on the one hand and Greece and Turkey on the other. They find that the joint external costs from $CO_2$ emissions (well-to-tank and tank-to-wheel), noise, congestion, and traffic accidents can decrease by 30% when 1559 trucks are replaced by 63 freight trains per week.

The Pinchasik et al. (2020) study translates the changes in transported weight and transport performance as presented in the previous section into changes in different types of emissions. In the policy scenario with the strongest increase in rail transport (and largest reductions in road and sea transport) the net reductions in $CO_{2,eq}$ emissions do not exceed 3,6%. In several scenarios they find increased air pollutant emissions due to increases in sea transport, which has relatively high emissions for $NO_x$ and PM.

### Position present study

In the current study we estimate both the MSP and the resulting change in external and infrastructure costs. Only TNO (2017) and Pinchasik et al. (2020) also include those two steps[1] in their study, while the remaining studies in Tables 1 and 2 analyse only one of the two steps.

In the studies related to the Netherlands, a modal shift from road to both, rail and inland waterways, is usually analysed. TNO (2017), only to rail, and Panteia (2019), only to inland waterways, consider one alternative transport mode. And Nocera et al. (2018), Vierth et al. (2019), Boehm et al. (2021), and Janic and Vleugel (2012) do not include inland waterways as an alternative because this transport mode is not available on the corridors they consider.

The focus of most studies pertaining to the Netherlands is on the freight transport corridors. However, no more than two corridors are included in each study, and the North corridor has not been included in any previous study. We include all four corridors.

Regarding cargo segments, the existing literature focuses on cargo that is already in containers, or that can be containerised. In the current study, the MSP is estimated for both the container segment and the non-container segment (consisting of general cargo, dry bulk, and liquid bulk).

Finally, as explained in 'Scope', we include various uncertainties in our research. This uncertainty aspect is ignored in the existing literature.

Considering all points raised, we conclude that the present study is more extensive in scope than the discussed modal shift studies.

## Methodology

In the introduction we have described the three research steps we have taken. In this section we describe the methodology for each step.

[1] TNO (2017) limits itself to the analysis of modal shift from road to rail only, and includes one sole external effect, GHG emissions. Pinchasik et. al. (2020) consider only GHG emissions and air pollutant emissions.

**Step 1: determine the modal shift potential**

In short, the 'Modal Shift Potential' (MSP) is the (share of the) transported weight by road that could have been transported at, at least 10% lower costs by rail or inland waterways. First, we determine the so called reference modal splits for the years 2018 and 2050. For 2050 we determine two reference modal splits. One is based on the High growth scenario and the other on the Low growth scenario of the Welfare and Living Environment (WLO) outlook study (van Eck et al. 2020; van Meerkerk et al. 2020; PBL and CPB 2015; CPB and PBL 2015). The WLO scenarios for 2050 are 'policy-poor'[2] scenarios that cover a realistic bandwidth for the development of the population, economy, and also (freight) transport in the Netherlands. This makes the scenario's useful for calculating the effects of additional (modal shift) policy. The reference modal splits are calculated using the strategic freight transport model BasGoed. See Appendix B for a brief description of the functioning of BasGoed. The reference modal splits are determined for each combination of origin–destination in Fig. 1 and commodity groups in BasGoed (13 groups). The modal split module in this model divides the cargo over the transport modes using a mode choice model. We have determined the private transport costs for 2050 by applying growth factors to the cost figures for 2018. For example, the growth factors for the distance-related costs for road transport have been determined on the basis of the growth of energy costs based on the WLO scenarios.

By using a High and a Low scenario, we take into account uncertainty regarding, for example, economic growth and population growth and their effects on the amount of freight transport (per transport mode).

Next we determine the three alternative modal splits (one for 2018, two for 2050).

First, for all freight transport by road in the reference situation we calculate for each combination of origin–destination and commodity group what the transport costs would have been if the road cargo would be transported by rail and inland waterways. Herewith, we take into account the costs of pre- and end-haul by road, the time costs of transshipment, and the additional costs of the increase in total trip length of the shifted cargo. The shipment size of the cargo is not explicitly modelled. It is assumed that the shifted road-cargoes can be bundled into larger shipments for transport by rail and inland waterways. We realize this is often hard to establish. In the Netherlands so-called 'logistics brokers' are employed to bring together cargo's from different shippers. So, in the end we have three cost estimates (for road, rail, and inland waterways) for each combination. In Appendix C we present the cost functions for the different transport modes. Next, for each combination of origin–destination and commodity group, we compare the transport costs of road, rail and inland waterways. On combinations of origin–destination and commodity group where the cost difference with road transport is 10%[3] or more in favour of rail or inland waterways, all freight transport by road shifts to the transport mode with the lowest transport costs. On combinations of origin–destination and commodity group where the costs advantage of rail and inland shipping is less than

[2] They only take into account already proposed mobility policy (including investments in infrastructure) up to 2030, as laid down in the MIRT, the Multi-year Infrastructure, Spatial Planning and Transport Program (CPB and PBL, 2015). After 2030, the networks will remain as they are.

[3] The limit value of 10% is also used in Dat.mobility and Districon (2021) and established in consultation with parties from the freight transport sector. The idea behind the 10% threshold is that shippers want a certain minimum compensation for the money and time they spend to achieve a modal shift.

10% the cargo will remain with road. Each corridor is formed by a set of origin–destination combinations. We therefore sum the transported weight per transport mode of all combinations of origin–destination and commodity groups that belong to the same corridor to find the alternative modal split per corridor.

The alternative modal splits are based only on the transport costs of freight transport. The reference modal splits are based on both, transport costs and other factors that play a role in the choice of a particular mode of transport. The difference in both modal splits can therefore be interpreted as the maximum achievable modal shift when all non-transport cost barriers are removed: the Modal Shift Potential (MSP).[4] The 'other factors' are very diverse. Think of lower flexibility and transport speed of rail and inland shipping, or congestion in ports for inland ships.

The MSP's imply more freight transport on the railway and inland waterway networks and more transshipment. Therefore, we check in a last step if the additional cargo due to the MSP's can be fully accommodated on those networks and on the terminals. For the threshold values for the maximum capacity of the railway and waterway networks and the terminals we rely on Dat.mobility and Districon (2021).

#### Step 2: determine differences in external costs and infrastructure costs for the government per transport performance (tonkm)

We use different sources for figures of unit external costs of freight transport. For the Netherlands (CE Delft 2022a) a more recent study is available for unit cost figures for the six external effects for the year 2018 than for the former EU-28 (CE Delft 2019a). We use the unit external cost figures for the Netherlands for the Dutch part of the freight transport corridors and the unit cost figures for the former EU-28 for the non-Dutch part of the freight transport corridors.[5]

CE Delft (2022a) also contains 2018 figures for unit infrastructure costs for the Netherlands, but not for infrastructure charges, while we need both to determine the unit infrastructure costs for the government. For the figures for unit infrastructure costs and charges for 2018, we therefore use CE Delft (2019b, 2019c) for both the Dutch and non-Dutch part of the freight transport corridors.

Unit external cost figures for 2050 for the Netherlands for the two scenarios of the Welfare and Living Environment outlook study we retrieve from CE Delft (2022b). Due to a lack of data, unit infrastructure cost for the government for 2050 for the Netherlands are assumed equal to those for 2018.

[4] A modal shift (part of the MSP) may also be achieved by means of modal shift measures that further decrease the transport costs of rail and inland waterway transport. This may happen if some shippers are willing to accept the disadvantages of non-transport cost obstacles in return for lower transport costs. Example: a freight flow which is transported by road, but which can be transported against 11% lower cost by rail, may not only shift when the non-transport cost obstacle (a low reliability of the rail service for example) is removed, but also if the transport cost advantage for rail is further increased to let's say 20%, without removing the non-transport cost obstacle (the low reliability of the rail service remains). So, instead of removing all non-transport cost obstacles to achieve the MSP, some of those obstacles could, in theory, be overcome by larger transport cost advantages. In practice however, for cargo flows by road that could be transported at significant lower costs (let say 20% or more) by rail or inland waterways, a further increase in the transport cost gap is not very likely to result in a shift. If the transport costs gap is already that large, it is more likely that non-transport cost obstacles form the bottleneck for modal shift.

[5] Because the output of the MSP analyses does not show how the foreign part of the transport performance on the freight transport corridors is distributed over the different (EU)-countries, we cannot determine weighted (on the basis of countries) average figures for external costs for the foreign part of the freight transport corridors. Therefore, we consider the former EU-28 figures as the best approximation of unit external costs of freight transport on the corridors outside of the Netherlands.

Next, an important choice to make is which unit costs we use: average costs or marginal costs? CE Delft (2019a, c, 2022a) provide average costs, and marginal costs for different situations. In general, because measures for modal shift lead to changes in existing traffic flows (and thus to changes in the magnitude of the external effects), the use of marginal costs is the most obvious choice. For each external effect, we judge which cost figure best suits the situation on the four freight transport corridors:

- For the external effects greenhouse gas emissions (tank-to-wheel), air pollutant emissions (tank-to-wheel), well-to-tank emissions of greenhouse gases and air pollution, and for traffic accidents for the transport modes rail and inland shipping, the average costs are equal to the marginal cost and we don't have to make a choice.
- Traffic accidents (road transport): we choose the marginal costs for the 'motorway' situation because freight transport on the corridors mainly takes place on motorways.
- Noise: we opt for weighted average marginal costs for freight transport through rural and urban areas, during the day and night, and at busy and quiet times, because all these situations apply to the freight transport corridors from time to time.
- Congestion: marginal external congestion costs are available in CE Delft (2022a) for three levels of congestion and for different types of roads. Most of the time, however, there is no congestion on the roads of the freight corridors. An extra road vehicle does then not cause extra congestion (the marginal congestion costs are equal to zero). For this reason we do not choose one of the possible marginal external congestion costs, but for average external congestion costs. Because freight transport on the corridors mainly takes place on motorways, we have chosen the cost figure for average external congestion costs on motorways. We opt for the external congestion costs according to the deadweight loss concept.
- For the infrastructure costs for the government, we subtract the variable infrastructure charges from the variable part of the average infrastructure costs (or the marginal infrastructure costs). 'Variable' means that these costs and charges depend on the level of use. The user-dependent infrastructure costs include part of the maintenance and part of the renewal costs (CE Delft 2019c, p.26). For road freight transport, we opt for cost figures that apply to motorways.

#### Step 3: estimate change in external costs and infrastructure costs for the government due to MSP's

We developed a model that first calculates the difference in transport performance per transport mode between the reference modal split and the alternative modal split. Step 1 explains how these modal splits are determined. In the alternative situation, the transport performance for road is lower than in the reference situation. For rail and inland shipping, the transport performance in the alternative situation is higher than in the reference situation. Next, for each transport mode, we multiply the differences in transport performance with the mode-specific figures for external costs and infrastructure costs for the government. Finally, we sum the change of external costs and infrastructure costs for the government across all modes to find the total change of these costs.

**Table 3** Explanation of the symbols in Eqs. (1)–(7)

| Symbol | Description |
|---|---|
| Δtonkm | Change in transport performance |
| ref | Reference situation |
| alt | Alternative situation |
| Δ€ | Change in external costs |
| i | Type external effect |

In formula form:

$$\Delta tonkm_{road} = tonkm\_ref_{road} - tonkm\_alt_{road} \tag{1}$$

$$\Delta tonkm_{rail} = tonkm\_ref_{rail} - tonkm\_alt_{rail} \tag{2}$$

$$\Delta tonkm_{IWT} = tonkm\_ref_{IWT} - tonkm\_alt_{IWT} \tag{3}$$

$$\Delta €_{road} = \Delta tonkm_{road} * \left( \sum_i €tonkm_{road_i} \right) \tag{4}$$

$$\Delta €_{rail} = \Delta tonkm_{rail} * \left( \sum_i €tonkm\_rail_i \right) \tag{5}$$

$$\Delta €_{IWT} = \Delta tonkm_{IWT} * \left( \sum_i €tonkm\_IWT_i \right) \tag{6}$$

$$\Delta € = \Delta €_{road} + \Delta €_{rail} + \Delta €_{IWT} \tag{7}$$

Table 3 explains the symbols used in Eqs. (1)–(7).

## Results

Like the previous section, also this section is structured around the three research steps.

### Modal shift potentials 2018

For the container segment, the MSP on the international freight corridors is 36% in 2018. We regard the results for 2018 to be also representative for the coming years (near future) because differences in private transport costs between the transport modes change slowly over time. The breakdown by rail and inland waterways is 27% and 9% respectively. For non-container transport by road the MSP is 47%, with a breakdown of 5% by rail and 42% by inland waterways. Figure 5 visualizes the MSPs. Important for the interpretation of the MSPs is that the transported weight by road on the freight transport corridors in the Netherlands is approximately 10% of the total weight transported by road in the Netherlands. The MSP in both, the container and the non-container segment, is concentrated in the commodity groups (1) Agricultural, forestry and fishery

products, (2) Chemical products, (3) Food and luxury goods, (4) Machines, electronics, and transport vehicles, and (5) Other goods.

Figures 6, 7, 8 and 9 show how the MSP's change the transport performance of the transport modes on the corridors for both segments. First, the road share is already low in the reference modal splits because the corridors contain high capacity and high quality rail and inland waterway connections. If the MSP are fully realized the road share can drop further, from 16 to 6% in the container segment and from 30 to 6% in the non-container segment.

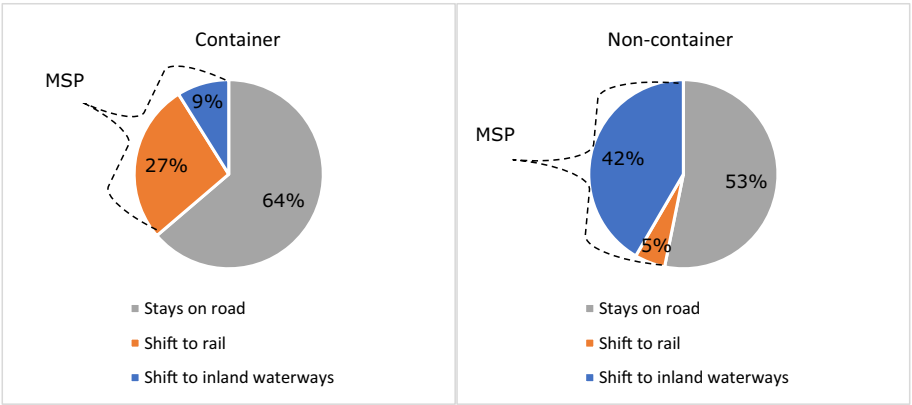


**Fig. 5** MSP of transported weight (ton) on the road on freight transport corridors East, Southeast, South, and North, 2018

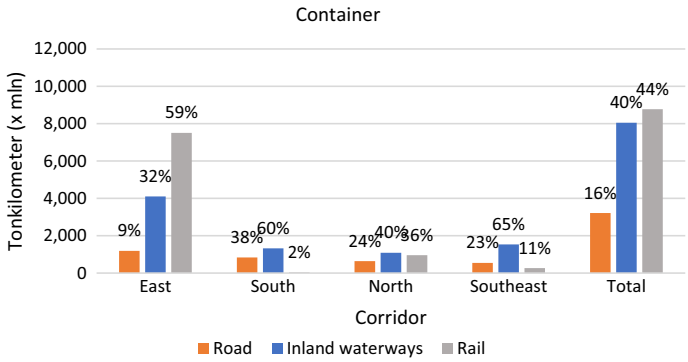


**Fig. 6** Reference modal split in transport performance (tonkm) for the container segment, 2018

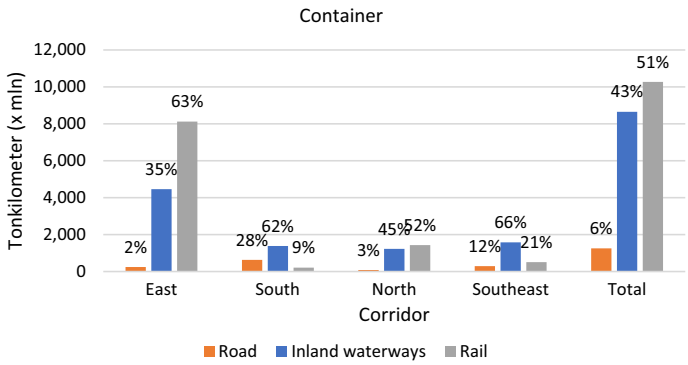


**Fig. 7** Alternative modal split (MSP realized) in transport performance (tonkm) for the container segment, 2018

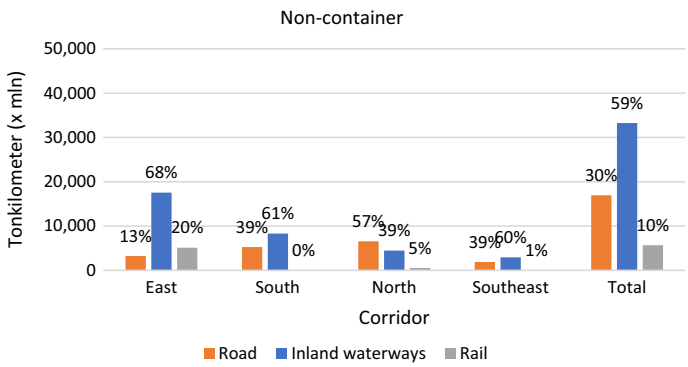


**Fig. 8** Reference modal split in transport performance (tonkm) for the non-container segment, 2018

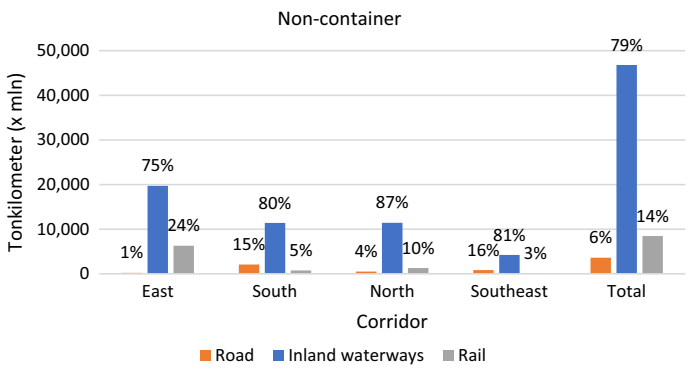


**Fig. 9** Alternative modal split (MSP realized) in transport performance (tonkm) for the non-container segment, 2018

### Modal shift potentials 2050

For the more distant future (2050), we have mapped the MSPs on the international freight transport corridors for the High and Low scenarios of the Welfare and Living Environment (WLO) outlook study. Figures 10 and 11 show the relative MSPs for 2050, broken down by rail and inland waterways. In the container segment rail takes over most cargo while in the non-container segment it is inland waterways that consumes the largest part of the MSP. The relative MSP in the Low scenario is larger than in the High scenario because in the High scenario the rail network and the terminals are confronted with capacity shortages. However, the absolute size of the MSP's (in transported weight) is larger in the High scenario than in the Low scenario. In 2050, the MSP is concentrated in the same commodity groups as in 2018.

The changes in modal shares based on transport performance of the four corridors together are presented in Table 4. The shares and shifts in both scenarios are comparable to those for 2018. The road shares drop around 10% (container segment) and 30%-35% (non-container segment to 3%-4% (container segment) and 6%-8% (non-container segment).

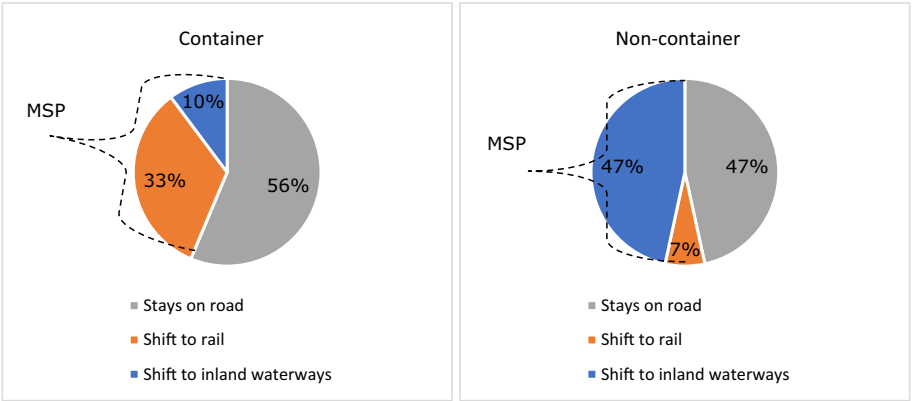


**Fig. 10** MSP of transported weight on the road on freight transport corridors East, Southeast, South, and North, 2050 WLO scenario low

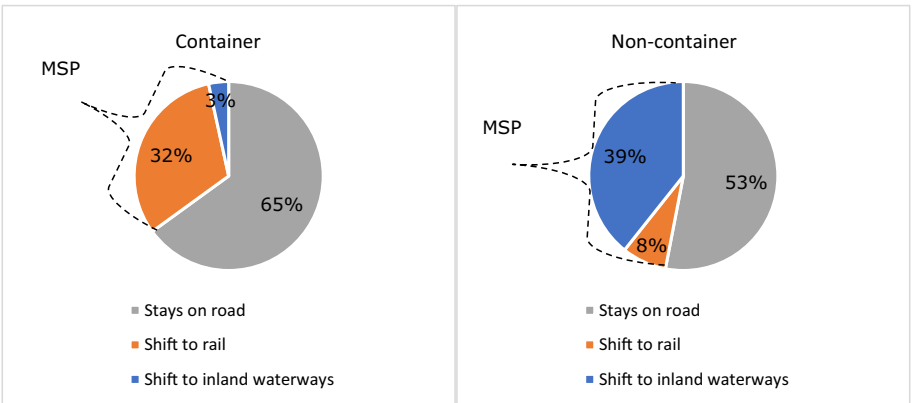


**Fig. 11** MSP of transported weight on the road on freight transport corridors East, Southeast, South, and North, 2050 WLO scenario high

**Table 4** Modal shares for 2050 total (all corridors) in reference modal split and alternative modal split (MSP realized), based on transport performance (tonkm)

| Scenario | Container | | | Non-container | | |
|---|---|---|---|---|---|---|
| | Road (%) | Inland waterways (%) | Rail (%) | Road (%) | Inland waterways (%) | Rail (%) |
| 2050 High reference | 11 | 36 | 53 | 34 | 55 | 10 |
| 2050 High alternative | 4 | 37 | 59 | 8 | 74 | 18 |
| 2050 Low reference | 10 | 40 | 49 | 32 | 57 | 10 |
| 2050 Low alternative | 3 | 42 | 55 | 6 | 79 | 16 |

**Table 5** Unit external costs and unit infrastructure costs for government for freight transport on corridors East, Southeast, South, and North in €-cent per tonkm, 2018, Netherlands and abroad. *Source*: CE Delft (2022a, 2019b, 2019c) and own calculations.

| Transport mode | Uncertainty | Traffic accidents | Air pollutant emissions | Greenhouse gas emissions | Noise | Congestion | Well-to-tank emissions | Total external costs | Infrastructure costs government | Total external costs + infrastructure costs government |
|---|---|---|---|---|---|---|---|---|---|---|
| *Netherlands* | | | | | | | | | | |
| Road | Upper bound | 0,43 | 1,70 | 1,14 | 0,07 | 0,59 | 1,12 | 5,05 | 0,67 | 5,72 |
| | Average | 0,33 | 1,10 | 0,69 | 0,06 | 0,52 | 0,57 | 3,27 | 0,57 | 3,84 |
| | Lower bound | 0,24 | 0,78 | 0,17 | 0,05 | 0,47 | 0,23 | 1,93 | 0,47 | 2,41 |
| Rail electric | Upper bound | 0,02 | 0,03 | 0,00 | 0,05 | 0,00 | 0,18 | 0,27 | 0,04 | 0,31 |
| | Average | 0,02 | 0,02 | 0,00 | 0,04 | 0,00 | 0,09 | 0,16 | 0,04 | 0,20 |
| | Lower bound | 0,01 | 0,01 | 0,00 | 0,03 | 0,00 | 0,02 | 0,08 | 0,03 | 0,11 |
| Rail diesel | Upper bound | 0,02 | 1,58 | 0,17 | 0,05 | 0,00 | 0,16 | 1,98 | 0,02 | 2,00 |
| | Average | 0,02 | 1,02 | 0,11 | 0,04 | 0,00 | 0,08 | 1,26 | 0,02 | 1,27 |
| | Lower bound | 0,01 | 0,72 | 0,03 | 0,03 | 0,00 | 0,03 | 0,82 | 0,01 | 0,83 |
| Inland waterways | Upper bound | 0,05 | 2,16 | 0,41 | 0,00 | 0,00 | 0,37 | 2,99 | 0,08 | 3,07 |
| | Average | 0,04 | 1,40 | 0,25 | 0,00 | 0,00 | 0,19 | 1,88 | 0,07 | 1,95 |
| | Lower bound | 0,03 | 0,99 | 0,06 | 0,00 | 0,00 | 0,07 | 1,16 | 0,06 | 1,22 |
| *Abroad* | | | | | | | | | | |
| Road | Upper bound | 0,87 | 1,21 | 0,90 | 0,05 | 0,54 | 0,40 | 3,98 | 0,36 | 4,34 |
| | Average | 0,67 | 0,78 | 0,55 | 0,04 | 0,48 | 0,21 | 2,72 | 0,31 | 3,03 |
| | Lower bound | 0,48 | 0,55 | 0,14 | 0,04 | 0,43 | 0,08 | 1,72 | 0,26 | 1,97 |
| Rail electric | Upper bound | 0,45 | 0,01 | 0,00 | 0,05 | 0,00 | 0,31 | 0,82 | 0,06 | 0,88 |
| | Average | 0,34 | 0,00 | 0,00 | 0,04 | 0,00 | 0,16 | 0,55 | 0,06 | 0,61 |
| | Lower bound | 0,24 | 0,00 | 0,00 | 0,03 | 0,00 | 0,04 | 0,32 | 0,05 | 0,37 |
| Rail diesel | Upper bound | 0,45 | 1,08 | 0,42 | 0,05 | 0,00 | 0,29 | 2,30 | -0,25 | 2,05 |
| | Average | 0,34 | 0,70 | 0,26 | 0,04 | 0,00 | 0,14 | 1,49 | -0,23 | 1,26 |
| | Lower bound | 0,25 | 0,50 | 0,06 | 0,03 | 0,00 | 0,05 | 0,89 | -0,20 | 0,70 |
| Inland waterways | Upper bound | 0,06 | 2,05 | 0,46 | 0,00 | 0,00 | 0,26 | 2,83 | -0,11 | 2,72 |
| | Average | 0,05 | 1,33 | 0,28 | 0,00 | 0,00 | 0,13 | 1,79 | -0,11 | 1,68 |
| | Lower bound | 0,04 | 0,94 | 0,07 | 0,00 | 0,00 | 0,05 | 1,10 | -0,09 | 1,01 |

#### Unit external costs and infrastructure costs

Drawing up figures for external costs and infrastructure costs for the government, as carried out by CE Delft (2019a, b, c, 2022a, b), is characterized by uncertainty. In those publications uncertainty margins are not provided though. The uncertainty lies in the valuation methods used, the data used and the assumptions made (CE Delft and VU 2014, p.36/37). For this reason, we have derived uncertainty bandwidths from CE Delft (2017) and CE Delft and VU (2014). These publications are from the same organization, and CE Delft (2022a, p.80) refers to the upper and lower bounds in CE Delft (2017) for 'application in social cost benefit analysis'. Another argument for calculating a bandwidth based on previous studies of the same organization is that the valuation methods used, the data used, and the assumptions made may become more accurate over time, as more research on valuation methods and data is carried out. With our bandwidths we are then on the 'safe side'. Consequently, we can show an upper bound and a lower bound value in Table 5 for freight transport on the corridors in the Netherlands and outside of the Netherlands ('abroad').

Doing some simple calculations we find that for both the Netherlands and the former EU-28 on average (abroad), the decrease in external costs plus infrastructure costs for the government per transport performance in 2018 is largest for a shift from road to rail-electric (NL: €0,0384–€0,0020, former EU-28: €0,0303–€0,0061), followed by a shift to rail-diesel (€0,0384–€0,0127, former EU-28: €0,0303—€0,0126), and finally a shift to inland waterways (€0,0384–€0,0195, former EU-28: €0,0303–€0,0168). If we look at the external costs only this order remains unchanged.

Some further results:

- For the former EU-28 on average, the marginal infrastructure costs for the government are negative for rail-diesel and inland waterways. This is because, according to CE Delft (2022b, c), for those modes the marginal infrastructure charges are higher than the marginal infrastructure costs.
- For the external effect of air pollutant emissions, a shift from road to inland waterways incurs an increase in external costs per transport performance for the Netherlands (+27%) and for the former EU-28 (+70%). This is because road transport (on the freight corridors) is cleaner on average per transport performance than inland waterways. The decrease in external costs of air pollutant emissions due to a shift from road to rail-diesel is small, with 7% for the Netherlands and 11% for the former EU-28.
- A shift from road to rail hardly leads to a cost reduction for the former EU-28 on the external effect of noise.

For 2050 (scenario's Low and High), we present the results in a much more condensed way (see Table 6). The results for each individual (external) effect can be found in Appendix D. Now, the reduction of external costs plus infrastructure costs in 2050 is largest for a shift from road to rail-electric, followed by a shift to inland waterways, and last a shift to rail-diesel.

**Table 6** Unit external costs and unit infrastructure costs for government for freight transport on corridors East, Southeast, South, and North in €-cent per tonkm, 2050, Netherlands, WLO scenario's low and high. *Source*: CE Delft (2022a, b, 2019b, c) and own calculations

| Transport mode | Uncertainty | Total external costs + infrastructure costs government, scenario low | Total external costs + infrastructure costs government, scenario high |
|---|---|---|---|
| Road | Upper bound | 4,07 | 9,57 |
| | Average | 2,89 | 6,75 |
| | Lower bound | 1,94 | 4,49 |
| Rail electric | Upper bound | 0,14 | 0,16 |
| | Average | 0,11 | 0,12 |
| | Lower bound | 0,08 | 0,09 |
| Rail diesel | Upper bound | 1,93 | 5,34 |
| | Average | 1,20 | 3,22 |
| | Lower bound | 0,70 | 1,68 |
| Inland waterways | Upper bound | 1,63 | 4,36 |
| | Average | 1,05 | 2,68 |
| | Lower bound | 0,64 | 1,44 |

### Changes in external costs and infrastructure costs with MSP's

We have seen that on the basis of the transport cost criterium, part of the transported weight by road on the freight corridors in North-western Europe can be shifted to rail and inland waterways (the MSP). In addition, the sum of the external costs and infrastructure costs for the government per transport performance on these corridors are higher for road transport than for rail and inland waterway transport. Therefore, in this section we calculate the change in external costs and infrastructure costs for the government in case the MSP's are fully realized, using the Eqs. (1)–(7) from the previous section.

Because the unit external cost figures for electric rail and diesel rail are different, we have to know how the MSP from road to rail is distributed over these two energy sources. For this we base ourselves on the information in Table 7. The shares of electric and diesel rail on the foreign part of the corridors is a weighted average of the shares in the countries Germany, Belgium, France, Switzerland, Italy, Poland, Luxembourg, the Czech Republic and Slovakia. These are the countries through which the four corridors run.

**Table 7** Share electric and diesel rail. *Source*: CE Delft (2020, Table 49) en IRG Rail (2021, p.10)

| Energy source | Netherlands (%) | Abroad (%) |
|---|---|---|
| Electric | 73 | 64 |
| Diesel | 27 | 36 |

***Results 2018***

For the Netherlands, the largest cost reductions are achieved on the external effects greenhouse gas emissions and congestion. For air pollutant emissions, the external costs increase slightly. This is because the costs per transport performance for this external effect are higher for inland waterways than for road (see Table 4) and the MSP (total of container and non-container segment) to inland shipping is a factor four greater than the MSP to rail. The whiskers in Figs. 12 and 13 indicate the bandwidths as a result of uncertainty in the data, assumptions and valuation methods used for the unit cost figures. This uncertainty is particularly great for greenhouse gas emissions and well-to-tank emissions.

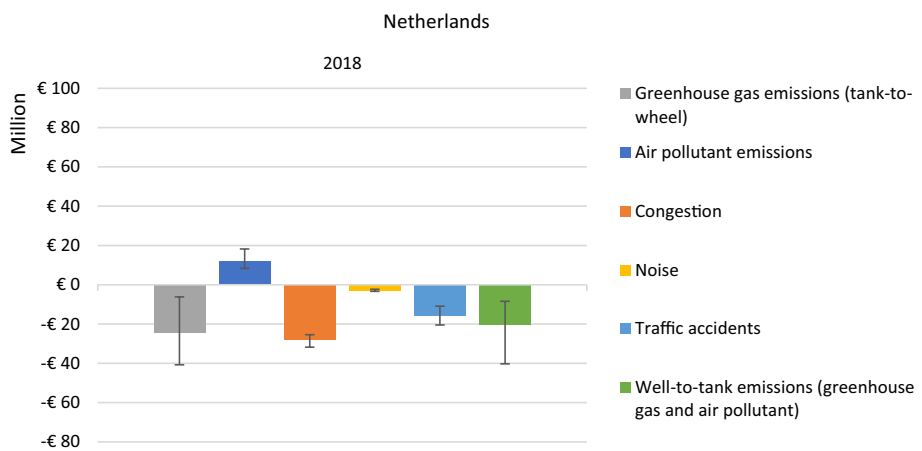


**Fig. 12** Change external costs in Netherlands when MSP's on freight transport corridors are fully realized, 2018

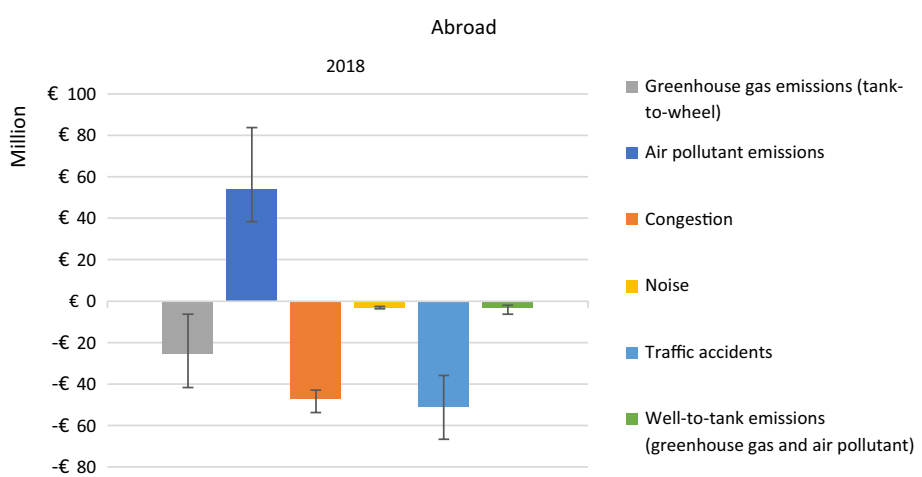


**Fig. 13** Change external costs outside Netherlands when MSP's on freight transport corridors are fully realized, 2018

Abroad, the largest cost reductions are realized on the external effects congestion and traffic accidents. Compared to the Netherlands, the greater cost increase on air pollutant emissions is striking. We can mention two reasons for this. Firstly, the size of the modal shift from road to inland shipping (and hence the decrease in road transport performance and the increase in inland waterway transport performance) is greater on the foreign part of the freight transport corridors than on the Dutch part. Secondly, the difference in external costs per transport performance for air pollutant emissions between road and inland shipping is greater for the former EU-28 than for the Netherlands (see Table 5).

If the entire MSP is realized, the bandwidth of the decrease in the total external costs of freight transport on the four corridors will be €45 million to €118 million for the Netherlands and €51 million to €88 million for the abroad part in 2018 (see the blue bar in Figs. 14, 15). The orange bars show the maximum change in infrastructure costs for the government. The cost reduction is €22 million to €32 million for the Netherlands and €35 million to €48 million for the abroad part. For the reduction of external costs and infrastructure costs for the government together, we find a bandwidth of €67 million to €150 million for the Dutch part and €86 million and €136 million for the abroad part.

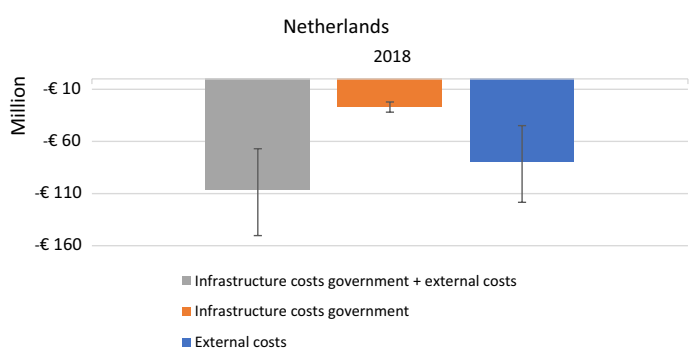


**Fig. 14** Change external costs and infrastructure costs for government in Netherlands when MSP's on freight transport corridors are fully realized, 2018

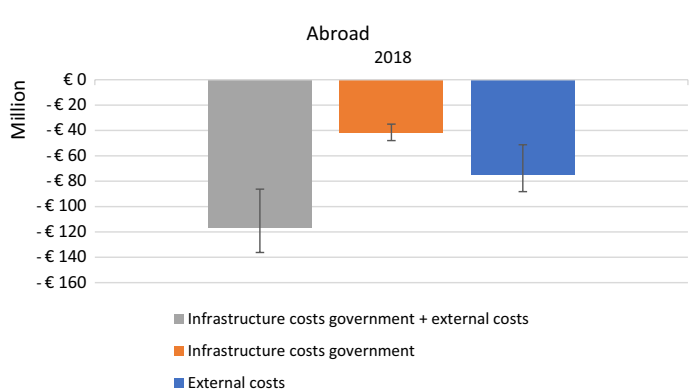


**Fig. 15** Change external costs and infrastructure costs for government outside Netherlands when MSP's on freight transport corridors are fully realized, 2018

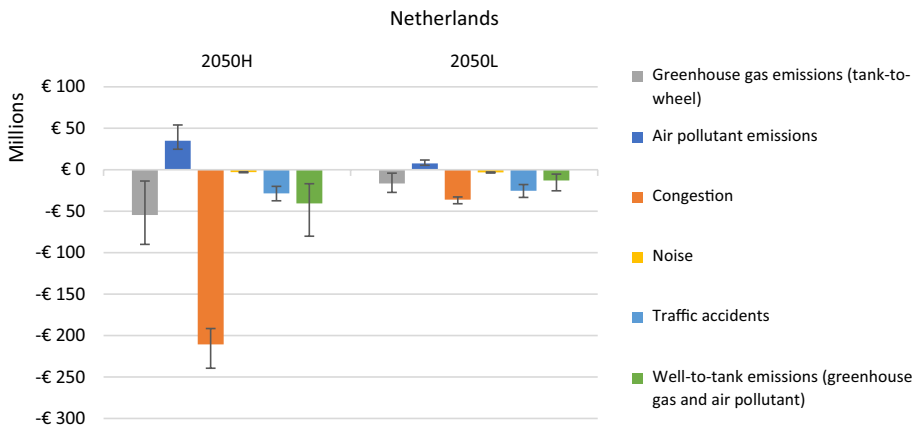


**Fig. 16** Change external costs in Netherlands when MSP's on freight transport corridors are fully realized, 2050

***Results 2050, base situation***

Unit external cost figures for 2050 for the former EU-28 are not available. Therefore, we perform analysis for the Dutch part of the freight transport corridors only.

According to Dat.mobility and Districon (2021, p.99) the share of diesel trains is 20% in 2050, in both scenario's of the Welfare and Living Environment outlook study. We adopt this percentage, instead of the 27% in the 2018 situation.

When the MSPs are realized the reduction in external congestion costs is largest in both scenario's (compared to the other external effects) and much larger in the High scenario than in the Low scenario, as shown by Fig. 16. There are several reasons for this difference between the scenario's. Firstly, in absolute terms, the MSP is larger in the High scenario. Secondly, congestion formation is strongly non-linear (CE Delft 2022b, p.104). This implies that in the High scenario much more road congestion is avoided by modal shift than in the Low scenario. Thirdly, the valuation of congestion depends on the economic situation (CE Delft 2022b, p.104). Because incomes are higher in the High scenario than in the Low scenario, hours that are not productive due to congestion are valued higher in the High scenario (CE Delft 2022b, p.105). Together, these causes are responsible for a factor of 5 to 6 higher external congestion costs in scenario High than in scenario Low.

Another observation from Fig. 16 is that the cost changes of GHG-emissions, air pollutant emissions, well-to-tank emissions due to the MSP's are also larger in the High scenario than in the Low scenario. Also the larger size of the MSP in the High scenario compared to the Low scenario plays a role here. Specific for GHG-emissions, the valuation (price) of a ton $CO_2$ is higher in the High scenario than in the Low scenario (because the High scenario involves more climate policy).

In Fig. 17 we see a major difference between the High and Low scenario's regarding the reduction of total external costs, and the sum of external costs and infrastructure costs for the government. The difference in decrease in external congestion costs between the two scenario's is largely responsible for this. In the High scenario the decrease in infrastructure costs for the government due to the MSPs is modest compared to the decrease in external costs.

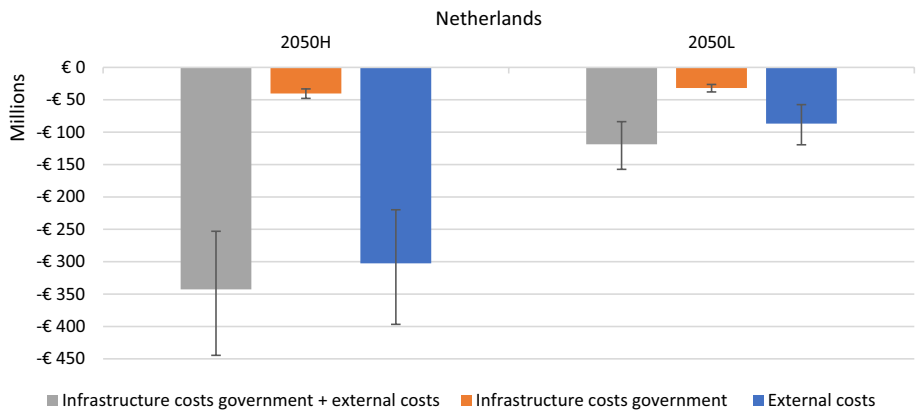


**Fig. 17** Change external costs and infrastructure costs for government in Netherlands when MSP's on freight transport corridors are fully realized, 2050

The maximum decrease in external costs and infrastructure costs for the government together in the High scenario ranges from €253 million to €444 million and in WLO-Low from €84 million to €157 million. These results show that the differences in assumptions between the High and Low scenario (regarding population and economic growth, but also the amount of climate policy for example) have a major impact on the size of the reduction of external costs and infrastructure costs for the government of freight transport on the freight transport corridors in the Netherlands that can be achieved by realizing the MSP's.

#### *Sensitivity analyses 2050*

As explained in "Methodology" section, the scenarios of the Welfare and Living Environment Outlook study are 'policy-poor' scenarios, which makes them useful for calculating the effects of additional policy. In the next two sensitivity analyses we exploit this characteristic of the scenarios. The goal of those analyses is to find out how sensitive the above results for 2050 are for changes in the starting points of the scenarios, i.e. for additional policies and innovations from the freight transport market.[6] Such changes may affect (1) the external costs and infrastructure costs for the government per transport performance and (2) the (private) transport costs for the shippers (as a result of which the MSP's can change). A limitation of the sensitivity analyses is that we can only take into account the first type of sensitivity because we don't know how the private transport costs are affected.

#### *What-if-situation 1: 'freight transport is zero-emission'*

Zero-emission implies a situation in which freight transport no longer generates greenhouse gas emissions (tank-to-wheel), air-pollutant emissions (tank-to-wheel) and well-to-tank emissions. Due to an ambitious climate and environmental policy, resulting in freight vehicles that are all powered by climate-neutral energy sources, this situation

[6] Examples of additional policies: subsidies on the production of zero-emission trucks, new road pricing schemes, and electrification of all non-electrified rail tracks. Examples of innovations from the market: new hull designs for inland ships and electric road systems (ERS).

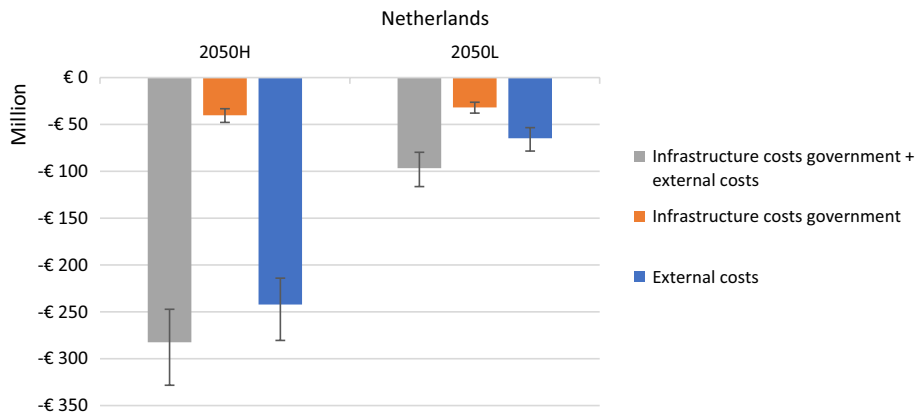


**Fig. 18** Change external costs and infrastructure costs for government in Netherlands when MSP's on freight transport corridors are fully realized, and freight transport is zero-emission, 2050

may occur in the more distant future. The costs of the aforementioned external effects of freight transport on the four freight transport corridors are then equal to zero and thus, modal shift cannot reduce these costs. The magnitude of the maximum (based on the MSPs) cost changes for the external effects congestion, noise and traffic accidents is not affected by a zero-emission situation and remain as they are in the base situation.

The size of the maximum reduction of infrastructure costs for the government in this sensitivity analysis is also the same as in the base situation. As presented in Fig. 18, the decrease in the total of external costs and infrastructure costs for the government the High scenario amounts to €247 million to €328 million. The bandwidth in Low scenario is €79 million to €116 million.

If, in addition to the external costs due to emissions, also the external congestion costs disappear completely due to additional policy on road pricing for example, the maximum decrease in the total of external costs and infrastructure costs is still €55 million to €88 million in the High scenario, and €46 million to €74 million in the Low scenario (not shown in a figure).

#### *What-if-situation 2: 'inland waterways more pollutant + road infrastructure charge'*

In this second sensitivity analysis, road, rail, and inland waterways still have 25% well-to-tank emissions. In addition, GHG-emissions and air pollutant emissions (both tank-to-wheel) by inland waterways are 25% of the level in the base situation for 2050 (while they are zero for road and rail). Next, there is a road charge of €0,15 per km which is labelled as an infrastructure charge, so that the revenues of this charge are deducted from the marginal road infrastructure costs. As a result the infrastructure costs for the government per transport performance become negative (the government earns a 'profit' on each tonkm of road transport).[7] Both changes compared to the base situation imply that modal shift results in a cost increase on some (external) effects, but not on others, as shown in Figs. 19 and 20.

[7] This road charge was also present in the previous what-if-situation and in the base situation, but there it was labelled as an 'innovation and sustainability' charge. This means that the revenues from the charge are returned to the freight transport sector to make freight vehicles more sustainable. Consequently, the revenues could not be used to lower the marginal road infrastructure costs.

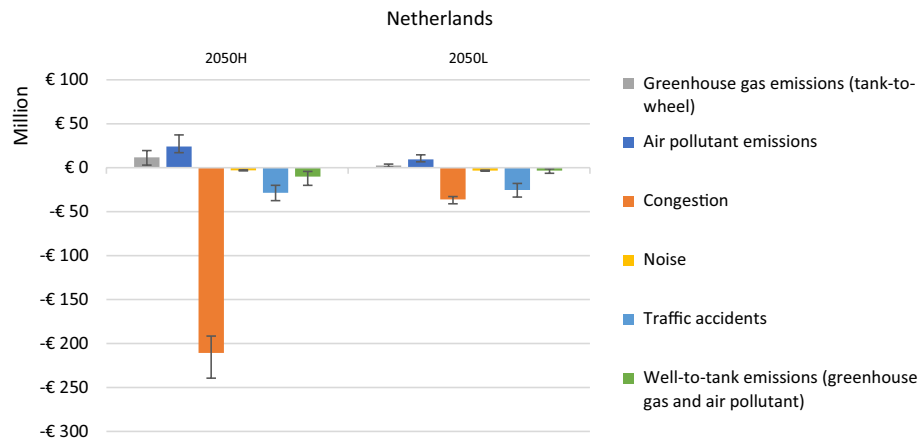


**Fig. 19** Change external costs in Netherlands when MSP's on freight transport corridors are fully realized, with 25% WTT emissions all modes + inland waterways still 25% TTW emissions, + road infrastructure charge, 2050

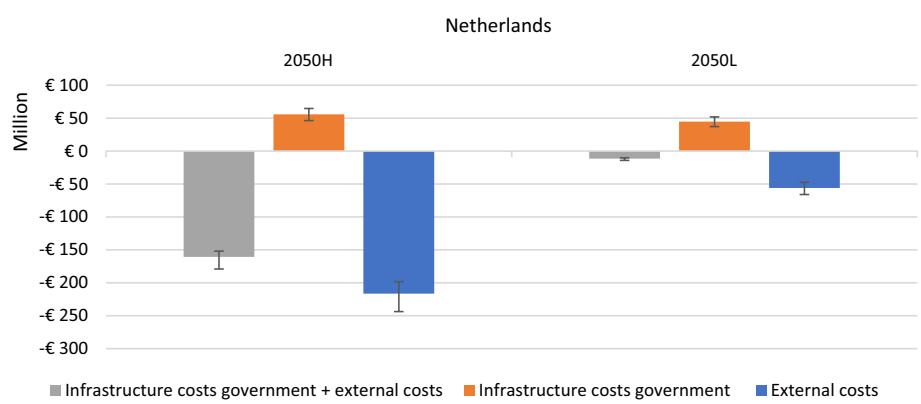


**Fig. 20** Change external costs and infrastructure costs for government in Netherlands when MSP's on freight transport corridors are fully realized, with 25% WTT emissions all modes + inland waterways still 25% TTW emissions, + road infrastructure charge, 2050

In scenario High a substantial reduction of the external congestion costs ensures that there is still a significant decrease in the total of external costs and infrastructure costs for the government of €152 million to €178 million upon realization of the MSP's. In scenario Low the decrease in external congestion costs is limited, so that the maximum bandwidth of the decrease in the total of infrastructure costs for the government and external costs is (only) approximately €11 million to €14 million. Now suppose that the external congestion costs are equal to zero because of additional policy on accessibility. Then there will be an increase in the sum of the external costs and infrastructure costs for the government of €39 million to €60 million in scenario High, and €22 million to € 27 million in scenario Low (not shown in a figure).

## Conclusion

This paper investigates whether policy efforts on modal shift can reduce the external costs and infrastructure costs for the government from freight transport on four corridors in North-western Europe, now and in the future further away. The share of road transport (in transported weight) on the corridors in the Netherlands in total road transport in the Netherlands is about 10%.

First we find that part of the transported weight by road on those corridors could be transported against at least 10% lower costs by rail or inland waterways. We call this part the Modal Shift Potential (MSP). We find MSP's of between 35 and 55%, depending on the market segment (container, or non-container transport), and year. These percentages may look substantial but we emphasize that on the freight transport corridors, rail and inland waterways are more competitive to road than outside of these corridors.

Next, it appears that the unit external costs and infrastructure costs per transport performance (tonkm) for road transport are higher than those for rail and inland waterway transport. The costs of the following external effects are included: greenhouse gas emissions (tank-to-wheel), air pollutant emissions (tank-to-wheel), noise, traffic accidents, congestion, and emissions from fuel and electricity production (well-to-tank) for freight vehicles.

Last, we calculate the changes in external costs and infrastructure costs that result from the MSP's. We emphasize that the amounts presented are maximum annual savings which can only be achieved if the MSP's are fully realized, which means that all non-transport cost obstacles for modal shift must be removed. Our analyses show a decrease in external- and infrastructure costs of €67 million to €150 million for the Netherlands, and €87 million to €136 million outside of the Netherlands for 2018. For 2050 estimating a maximum and minimum for the change in external- and infrastructure costs is not possible due to uncertainties in the development of the transport costs and the external costs of freight transport. Considering these results, we conclude that at the moment, and likely also in the coming few years, policy efforts on modal shift on the freight transport corridors in North-western Europe can be effective. If we had found that the MSP's are (close to) zero, or that the external costs per tonkm for road are equal to, or lower than those for rail and inland waterways, then our conclusion for 2018 would have been: 'Policy efforts on modal shift cannot be effective'.

We stress that the results we present, in terms of MSP's and the corresponding changes in external costs, are unique for the freight corridors and cannot be generalized to other spatial contexts (the Netherlands at the country level, or other corridors in Europe for example). After all, in other spatial contexts the availability of infrastructure, the size and composition of the cargo flows, and the length of corridors for example will be different.

### Focus points for policy makers

An important focus point follows from the main conclusion that policy efforts on modal shift[8] can be effective in the coming years. This implies that investing in modal shift

[8] An example of a set of modal shift measures in the Netherlands taken in 2021 was (1) the provision of a subsidy for shippers to help them making the step to rail and inland waterways and (2) a tender to increase the supply of frequent liner services in inland waterway transport (see: https://connekt.nl/programma-initiatief/modal-shift-programma/ (in Dutch)).

measures with a payback period of several years can be well defended. For measures with a long payback period this is questionable because additional policy (in the field of sustainability or accessibility, for example) may mute the reduction of external costs and infrastructure costs for the government through modal shift. This implies that the costs and benefits of measures in the freight transport market must be evaluated in their interdependency.

The savings on external costs and infrastructure costs for the government based on the MSPs are only possible if the estimated MSPs are fully realized. That is probably impossible because, in addition to minor barriers to modal shift, major barriers must also be removed then. This raises the question what the optimal amount and composition of modal shift measures is. It makes sense to first focus policy efforts on measures with relatively low costs and high benefits. As more measures are taken, it will be increasingly difficult to find measures with a positive balance of costs and benefits.

With regard to the external effect of air pollutant emissions, we find that the costs per transport performance are higher for inland waterways than for road. We also observe that the MSPs result in an increase in external costs for this effect. Apparently, the reduction in air pollutant emissions due to the shift to rail is more than canceled out by the increase in those emissions due to the shift to inland waterways. Consequently, the total decrease in external costs due to modal shift can increase if inland waterways can speed up the greening of the sector on the external effect of 'air pollutant emissions' compared to road.

Considering all external effects and the wear and tear of infrastructure, at the moment (2018, see Table 4) a shift to electric rail yields the largest cost reduction per transport performance (2,30 €-cent to 5,41 €-cent). This is followed by a shift to diesel rail (1,58 € cents to 3,72 € cents) and finally to inland shipping (1,19 € cents to 2,65 € cents). This means that prioritizing modal shift measures according to the mode of transport to which the cargo shifts can be useful, also taking into account the available capacity on the rail and inland waterway networks.

### Directions for further research

The MSP's show that non-transport cost barriers prevent a substantial share of road transport to shift to rail or inland waterways. Further research may focus on these barriers answering questions like "what are the main barriers", and "how can they be removed"?

Subsequently, research on the benefits, but also the costs of measures to remove those barriers comes into play. Assessing these costs is an important direction for further research. If the benefits (of which the decrease in external costs and infrastructure costs for the government are part) do not outweigh the costs, the studied measures are not efficient and cannot be justified from a welfare-economic point of view.

Follow-up research could also focus on fine-tuning the MSPs estimated here. It is likely that there are barriers to modal shift that cannot be removed. By finding out what those barriers are, and what part of the total size of the freight transport market they cover, part of the road transport on the freight transport corridors can be designated as 'non-shiftable' prior to the analysis. The MSPs will be smaller then.

Finally, this and earlier research on modal shift potential (see "Literature" section) relates to the East, Southeast, South and North freight transport corridors. We find that the transported weight by road on these corridors is approximately 10% of the transported weight by road in the Netherlands. This raises the question what the MSP is for the other 90% of road transport. It is expected to be smaller because rail and inland waterway are a less attractive alternative to the road outside the corridors than on the corridors.

## Appendix A: NUTS-3 regions included in the analysis

### Corridor North

Group 1

| Region code | Region name | Country |
|---|---|---|
| NL339 | Overig Groot Rijnmond | Netherlands |
| NL339 | Waal_Eemshaven | Netherlands |
| NL339 | Pernis | Netherlands |
| NL339 | Botlek | Netherlands |
| NL339 | Europoort | Netherlands |
| NL339 | Maasvlakte_I_II | Netherlands |
| NL33A | Zuidoost-Zuid Holland | Netherlands |
| NL323 | IJmond | Netherlands |
| NL324 | Agglomeratie Haarlem | Netherlands |
| NL325 | Zaanstreek | Netherlands |
| NL326 | Groot-Amsterdam | Netherlands |
| NL337 | Agglomeratie Leiden | Netherlands |
| NL332 | Agglomeratie Den Haag | Netherlands |
| NL333 | Delft en Westland | Netherlands |
| NL338 | Oost-Zuid Holland | Netherlands |

Group 2

| Region code | Region name | Country |
|---|---|---|
| NL111 | Oost-Groningen | Netherlands |
| NL112 | Delfzijl en omstreken | Netherlands |
| NL113 | Overig Groningen | Netherlands |
| NL121 | Noord-Friesland | Netherlands |
| NL122 | Zuidwest-Friesland | Netherlands |
| NL123 | Zuidost-Friesland | Netherlands |
| NL131 | Noord-Drenthe | Netherlands |
| NL132 | Zuidoost-Drenthe | Netherlands |
| NL133 | Zuidwest-Drenthe | Netherlands |
| DE30 | Berlin | Germany |
| DE40 | Brandenburg | Germany |
| DE50 | Bremen | Germany |
| DE60 | Hamburg | Germany |
| DE80 | Mecklenburg-Vorpommern | Germany |
| DE91 | Braunschweig | Germany |
| DE92 | Hannover | Germany |

| Region code | Region name | Country |
|---|---|---|
| DE93 | Lüneburg | Germany |
| DE94 | Weser-Ems | Germany |
| DEA3 | Münster | Germany |
| DEA4 | Detmold | Germany |
| DEE0 | Sachsen-Anhalt | Germany |
| DEF0 | Schleswig–Holstein | Germany |
| PL11 | Lódzkie | Poland |
| PL12 | Mazowieckie | Poland |
| PL21 | Maléopolskie | Poland |
| PL22 | Slàskie | Poland |
| PL31 | Lubelskie | Poland |
| PL32 | Podkarpackie | Poland |
| PL33 | Swietokrzyskie | Poland |
| PL34 | Podlaskie | Poland |
| PL41 | Wielkopolskie | Poland |
| PL42 | Zachodniopomorskie | Poland |
| PL43 | Lubuskie | Poland |
| PL51 | Dolnosiàskie | Poland |
| PL52 | Opolskie | Poland |
| PL61 | Kujawsko-Pomorskie | Poland |
| PL62 | Warminäsko-Mazurskie | Poland |
| PL63 | Pomorskie | Poland |

## Corridor Southeast

### Group 1

| Region code | Region name | Country |
|---|---|---|
| NL339 | Overig Groot Rijnmond | Netherlands |
| NL339 | Waal_Eemshaven | Netherlands |
| NL339 | Pernis | Netherlands |
| NL339 | Botlek | Netherlands |
| NL339 | Europoort | Netherlands |
| NL339 | Maasvlakte_I_II | Netherlands |
| NL339 | Zuidoost-Zuid Holland | Netherlands |

### Group 2

| Region code | Region name | Country |
|---|---|---|
| NL412 | Midden-Noord Brabant | Netherlands |
| NL413 | Noordoost-Noord Brabant | Netherlands |
| NL414 | Zuidoost-Noord Brabant | Netherlands |
| NL421 | Noord-Limburg | Netherlands |
| NL422 | Midden-Limburg | Netherlands |
| NL423 | Zuid-Limburg | Netherlands |
| BE22 | Prov. Limburg (BE) | Belgium |
| BE33 | Prov. Liège | Belgium |

| Region code | Region name | Country |
|---|---|---|
| BE34 | Prov. Luxembourg (BE) | Belgium |
| BE35 | Prov. Namur | Belgium |
| FR21 | Champagne-Ardenne | France |
| FR26 | Bourgogne | France |
| FR41 | Lorraine | France |
| FR42 | Alsace | France |
| FR43 | Franche-Comté | France |
| FR71 | Rhône-Alpes | France |
| FR81 | Languedoc-Roussillon | France |
| FR82 | Provence-Alpes-Côte d'Azur | France |
| FR83 | Corse | France |
| LU00 | Luxembourg | Luxemburg |

**Corridor East**

Group 1

| Region code | Region name | Country |
|---|---|---|
| NL339 | Overig Groot Rijnmond | Nederland |
| NL339 | Waal_Eemshaven | Nederland |
| NL339 | Pernis | Nederland |
| NL339 | Botlek | Nederland |
| NL339 | Europoort | Nederland |
| NL339 | Maasvlakte_I_II | Nederland |
| NL33A | Zuidoost-Zuid Holland | Nederland |

Group 2

| Region code | Region name | Country |
|---|---|---|
| CH01 | Région lémanique | Switzerland |
| CH02 | Espace Mittelland | Switzerland |
| CH03 | Nordwestschweiz | Switzerland |
| CH04 | Zürich | Switzerland |
| CH05 | Ostschweiz | Switzerland |
| CH06 | Zentralschweiz | Switzerland |
| CH07 | Ticino | Switzerland |
| CZ01 | Praha | Czech Republik |
| CZ02 | StÖednîechy | Czech Republik |
| CZ03 | Jihozípad | Czech Republik |
| CZ04 | Severozípad | Czech Republik |
| CZ05 | Severovchod | Czech Republik |
| CZ06 | Jihovchod | Czech Republik |
| CZ07 | StÖedn Morava | Czech Republik |
| CZ08 | Moravskoslezsko | Czech Republik |
| DE11 | Stuttgart | Germany |
| DE12 | Karlsruhe | Germany |
| DE13 | Freiburg | Germany |
| DE14 | Tübingen | Germany |
| DE21 | Oberbayern | Germany |

| Region code | Region name | Country |
|---|---|---|
| DE22 | Niederbayern | Germany |
| DE23 | Oberpfalz | Germany |
| DE24 | Oberfranken | Germany |
| DE25 | Mittelfranken | Germany |
| DE26 | Unterfranken | Germany |
| DE27 | Schwaben | Germany |
| DE71 | Darmstadt | Germany |
| DE72 | Gießen | Germany |
| DE73 | Kassel | Germany |
| DEA1 | Düsseldorf | Germany |
| DEA2 | Köln | Germany |
| DEA5 | Arnsberg | Germany |
| DEB1 | Koblenz | Germany |
| DEB2 | Trier | Germany |
| DEB3 | Rheinhessen-Pfalz | Germany |
| DEC0 | Saarland | Germany |
| DED2 | Dresden | Germany |
| DED4 | Chemnitz | Germany |
| DED5 | Leipzig | Germany |
| DEG0 | Thüringen | Germany |
| ITC1 | Piemonte | Italy |
| ITC2 | Valle d'Aosta/Valle d'Aoste | Italy |
| ITC3 | Liguria | Italy |
| ITC4 | Lombardia | Italy |
| SK01 | Bratislavsk?¢ kraj | Slovakia |
| SK02 | Z?ípadn?® Slovensko | Slovakia |
| SK03 | Stredn?® Slovensko | Slovakia |
| SK04 | V?¢chodn?® Slovensko | Slovakia |

## Corridor South

### Group 1

| Regio nr | Regio | Land |
|---|---|---|
| NL339 | Overig Groot Rijnmond | Netherlands |
| NL339 | Waal_Eemshaven | Netherlands |
| NL339 | Pernis | Netherlands |
| NL339 | Botlek | Netherlands |
| NL339 | Europoort | Netherlands |
| NL339 | Maasvlakte_I_II | Netherlands |
| NL33A | Zuidoost-Zuid Holland | Netherlands |
| NL323 | IJmond | Netherlands |
| NL324 | Agglomeratie Haarlem | Netherlands |
| NL325 | Zaanstreek | Netherlands |
| NL326 | Groot-Amsterdam | Netherlands |
| NL337 | Agglomeratie Leiden | Netherlands |
| NL332 | Agglomeratie Den Haag | Netherlands |
| NL333 | Delft en Westland | Netherlands |
| NL338 | Oost-Zuid Holland | Netherlands |

| Regio nr | Regio | Land |
|---|---|---|
| NL341 | Zeeuws-Vlaanderen | Netherlands |
| NL342 | Overig Zeeland | Netherlands |

Group 2

| Regio nr | Regio | Land |
|---|---|---|
| NL411 | West-Noord Brabant | Netherlands |
| BE10 | Région de Bruxelles-Capitale / Brussels Hoofdstedelijk Gewest | Belgium |
| BE21 | Prov. Antwerpen | Belgium |
| BE23 | Prov. Oost-Vlaanderen | Belgium |
| BE24 | Prov. Vlaams-Brabant | Belgium |
| BE25 | Prov. West-Vlaanderen | Belgium |
| BE31 | Prov. Brabant Wallon | Belgium |
| BE32 | Prov. Hainaut | Belgium |
| FR10 | Île de France | France |
| FR22 | Picardie | France |
| FR23 | Haute-Normandie | France |
| FR24 | Centre | France |
| FR25 | Basse-Normandie | France |
| FR30 | Nord - Pas-de-Calais | France |
| FR51 | Pays de la Loire | France |
| FR52 | Bretagne | France |
| FR53 | Poitou–Charentes | France |
| FR61 | Aquitaine | France |
| FR62 | Midi-Pyrénées | France |
| FR63 | Limousin | France |
| FR72 | Auvergne | France |

## Appendix B: the BasGoed strategic freight transport model

BasGoed is a strategic freight transport model owned by the Ministry of Infrastructure and Water Management. The model is used to calculate the effects of economic developments and policy measures on freight transport by road, rail and water (inland waterways and maritime shipping). Because we focus on inland transport on freight corridors, we do not consider maritime shipping. Basgoed not only covers Dutch regions, but also foreign regions, so that cross-border freight transport can also be modeled. The model has a modular structure. The economics module translates trade tables into quantities of produced and consumed goods per zone/region (origins and destinations). The distribution module distributes the weight to be transported over the origin–destination relations. The modal split module then divides the cargo over the transport modes. This is done on the basis of utility functions for the different modes of transport. The essence of this approach is that the choice for a particular transport mode is the result of a trade-off between those modes on the basis of transport costs and other factors such as the reliability of delivery, frequency of the (rail) service, sensitivity to damage, etc. The effect of these 'other factors' on utility is taken into account by means of a mode-specific constant in the utility functions. This constant is negative for rail and inland waterway transport

and zero for road. Finally the trip module determines the number of trips per transport mode. The modal split and number of trips per mode of transport are determined for all existing combinations of origin–destination pairs and 13 types of goods. We refer to De Bok et al. (2018, 2022) for more information about BasGoed.

## Appendix C: cost functions

### Cost function road

cost_vrt = [DISTANCE_per_trip] * [cost_distance] + [TIME_per_trip] * [cost_time] + [cost_loading_unloading] * 2 + [tax_per_trip] + [toll_per_trip].

### Cost functions rail

cost_vrt = [DISTANCE_per_trip] * [cost_distance] + ([TIME_per_trip] + [transshipment_time]) * [cost_time] + [cost_loading_unloading] *2 + [infra charge_per_trip].

cost_vrt_pre-haul = [DISTANCE_per_trip] * [cost_distance] + [TIME_per_trip] * [cost_time] + [cost_loading_unloading] *2 + [tax_per_trip] + [toll_per_trip].

cost_vrt_end-haul = [DISTANCE_per_trip] * [cost_distance] + [TIME_per_trip] * [cost_time] + [cost_loading_unloading] * 2 + [tax_per_trip] + [toll_per_trip].

### Cost functions inland waterways

cost_vrt = [DISTANCE_per_trip] * [cost_distance] + ([TIME_per_trip] + [transshipment_time]) * [cost_time] + [cost_loading_unloading] *2.

cost vrt_pre-haul = [DISTANCE_per_trip] * [cost_distance] + [TIME_per_trip] * [cost_time] + [cost_loading_unloading]*2 + [tax_per_trip] + [toll_per_trip].

cost_vrt_end-haul = [DISTANCE_per_trip] * [cost_distance] + [TIME_per_trip] * [cost_time] + [cost_loading_unloading]*2 + [tax_per_trip] + [toll_per_trip].

### Required number of vehicles

number_vrt = [tons] / ([cap vehicle] * [average_load] * [fraction_loaded_vehicles]).

### Total costs

Total costs road = [cost_vrt road * number_vrt road].

Total costs rail = [cost_vrt rail * number_vrt rail] + [cost_vrt_pre-haul * number_vrt road] + [cost_vrt_end-haul * number_vrt road].

Total costs inland waterways = [cost_vrt inland waterways * number_vrt inland waterways] + [cost_vrt_pre-haul * number_vrt road] + [cost_vrt_end-haul * number_vrt road].

### Explanation

cost_vrt = cost per vehicle per trip.

cost_loading_unloading = time costs of loading and unloading.

[tons] = annual tonnage at a certain origin–destination combination.

[cap vehicle] = average vehicle capacity.

We correct the number of vehicles required because vehicles are not always fully loaded, and because vehicles sometimes have to drive/sail empty to be able to pick up cargo somewhere.

## Appendix D: unit external costs and infrastructure costs 2050

See Table 8.

**Table 8** Unit external costs and unit infrastructure costs for government for freight transport on corridors East, Southeast, South, and North in €-cent per tonkm, 2050 WLO scenario low and high, Netherlands. Source: CE Delft (2022a, b; 2019b, c) and own calculations

| Transport mode | Uncertainty | Traffic accidents | Air pollutant emissions | Greenhouse gas emissions | Noise | Congestion | Well-to-tank emissions | Total external costs | Infrastructure costs government | Total external costs + infrastructure costs government |
|---|---|---|---|---|---|---|---|---|---|---|
| *WLO scenario low* | | | | | | | | | | |
| Road | Upper bound | 0,57 | 0,79 | 0,70 | 0,07 | 0,64 | 0,63 | 3,40 | 0,67 | 4,07 |
| | Average | 0,44 | 0,51 | 0,42 | 0,06 | 0,56 | 0,32 | 2,31 | 0,57 | 2,89 |
| | Lower bound | 0,31 | 0,36 | 0,11 | 0,05 | 0,51 | 0,13 | 1,47 | 0,47 | 1,94 |
| Rail electric | Upper bound | 0,02 | 0,03 | 0,00 | 0,04 | 0,00 | 0,01 | 0,10 | 0,04 | 0,14 |
| | Average | 0,02 | 0,02 | 0,00 | 0,03 | 0,00 | 0,00 | 0,07 | 0,04 | 0,11 |
| | Lower bound | 0,01 | 0,02 | 0,00 | 0,02 | 0,00 | 0,00 | 0,05 | 0,03 | 0,08 |
| Rail diesel | Upper bound | 0,02 | 1,18 | 0,35 | 0,03 | 0,00 | 0,33 | 1,92 | 0,02 | 1,93 |
| | Average | 0,02 | 0,76 | 0,22 | 0,03 | 0,00 | 0,16 | 1,18 | 0,02 | 1,20 |
| | Lower bound | 0,01 | 0,54 | 0,05 | 0,02 | 0,00 | 0,06 | 0,69 | 0,01 | 0,70 |
| Inland waterways | Upper bound | 0,05 | 0,99 | 0,28 | 0,00 | 0,00 | 0,23 | 1,55 | 0,08 | 1,63 |
| | Average | 0,04 | 0,64 | 0,17 | 0,00 | 0,00 | 0,12 | 0,97 | 0,07 | 1,04 |
| | Lower bound | 0,04 | 0,45 | 0,04 | 0,00 | 0,00 | 0,05 | 0,58 | 0,06 | 0,64 |
| *WLO scenario high* | | | | | | | | | | |
| Road | Upper bound | 0,52 | 1,33 | 2,16 | 0,05 | 2,98 | 1,86 | 8,90 | 0,67 | 9,57 |
| | Average | 0,40 | 0,86 | 1,31 | 0,04 | 2,62 | 0,95 | 6,18 | 0,57 | 6,75 |
| | Lower bound | 0,28 | 0,61 | 0,33 | 0,03 | 2,38 | 0,38 | 4,01 | 0,47 | 4,49 |
| Rail electric | Upper bound | 0,02 | 0,06 | 0,00 | 0,03 | 0,00 | 0,01 | 0,12 | 0,04 | 0,16 |
| | Average | 0,02 | 0,04 | 0,00 | 0,02 | 0,00 | 0,00 | 0,08 | 0,04 | 0,12 |
| | Lower bound | 0,01 | 0,03 | 0,00 | 0,02 | 0,00 | 0,00 | 0,06 | 0,03 | 0,09 |
| Rail diesel | Upper bound | 0,02 | 2,60 | 1,42 | 0,03 | 0,00 | 1,26 | 5,33 | 0,02 | 5,34 |
| | Average | 0,02 | 1,68 | 0,86 | 0,02 | 0,00 | 0,63 | 3,21 | 0,02 | 3,22 |
| | Lower bound | 0,01 | 1,19 | 0,21 | 0,02 | 0,00 | 0,23 | 1,66 | 0,01 | 1,68 |
| Inland waterways | Upper bound | 0,05 | 2,16 | 1,13 | 0,00 | 0,00 | 0,93 | 4,28 | 0,08 | 4,35 |
| | Average | 0,04 | 1,40 | 0,69 | 0,00 | 0,00 | 0,48 | 2,61 | 0,07 | 2,68 |
| | Lower bound | 0,04 | 0,99 | 0,17 | 0,00 | 0,00 | 0,18 | 1,38 | 0,06 | 1,44 |

**Abbreviations**

| | |
|---|---|
| MSP | Modal shift potential |
| GHG | GreenHouseGas |
| TEU | Twenty foot equivalent unit |
| WLO | Welvaart en LeefOmgeving (welfare and living environment) |
| BasGoed | Basismodel Goederenvervoer (basic model freight transport) |
| EU | European Union |

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**Author contributions**
OJ: conceptualization, data analysis, methodology, visualization, writing. KF: data analysis, methodology, writing. LH: data analysis, methodology. All authors read and approved the final manuscript.

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**Availability of data and materials**
Figures on external costs and infrastructure costs can be found in the publications of CE Delft in the bibliography and in the corresponding Excel files. These files, as well as the figures on transport costs for road, rail and inland waterways, are available from the corresponding author on reasonable request.

## Declarations

**Competing interests**
The authors declare that they have no competing interests.

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**References**

Boehm M, Arnz M, Winter J (2021) The potential of high-sspeed rail freight in Europe: how is a modal shift from road to rail possible for low density high value cargo? Eur Transp Res Rev 13:4. https://doi.org/10.1186/s12544-020-00453-3
Boneschansker E, 't Hoen AL (1992) Externe kosten van goederenvervoer, Rijkswaterstaat, Adviesdienst Verkeer en Vervoer
CE Delft and VU (2014) Externe en infrastructuurkosten van verkeer, een overzicht voor Nederland in 2010. Delft
CE Delft (2017) Handboek milieuprijzen 2017. Delft
CE Delft (2019a) Handbook on the external costs of transport. Delft
CE Delft (2019b) Transport taxes and charges in Europe. Delft
CE Delft (2019c) Overview of transport infrastructure expenditures and costs. Delft
CE Delft (2020) STREAM Goederenvervoer 2020. Emissies van modaliteiten in het goederenvervoer. Delft
CE Delft (2022a) De Prijs van een reis, Editie 2022a. CE Delft, Delft
CE Delft (2022b) Toekomstverkenning. De prijs van een reis. Verkennende analyse richting 2050. CE Delft, Delft
CPB and PBL (2015) Toekomstverkenning Welvaart en Leefomgeving, Cahier Mobiliteit, PBL-publicatienummer 1686
Dat.mobility en Districon (2021) Integrale Mobiliteitsanalyse, Achtergrondrapportage, Goederenvervoer Integraal, 22 april 2021
De Bok M, de Jong G, Tavasszy L, van Meieren J, Davydenko I, Benjamins M, Groot N, Miete O, van den Berg M (2018) A multimodal transport chain choice model for container transport. Transp Res Procedia 31:99–107
De Bok M, de Jong G, Wesseling B, Meurs H, van Bekkum P, Mijjer P, Bakker D, Veger T (2022) An ex-ante analysis of transport impacts of a distance-based heavy goods vehicle charge in the Netherlands. Res Transp Econ 95:101091
EC (2019) The European Green Deal. European Commission, Brussels
European Union (2020) Final Report MARCO POLO II PROGRAMME 2007–2013. Publications Office European Union. https://doi.org/10.2840/024488
Havenga JH, Simpson ZP (2018) Freight logistics' contribution to sustainability: systemic measurement facilities behavioural change. Transp Res Part D 58:320–331
ITF (2022) Mode choice in freight transport, ITF research reports. OECD Publishing, Paris
Janic M, Vleugel J (2012) Estimating potential reductions in externalities from rail-road substitution in Trans-European Freight transport corridors. Transp Res Part D 17:154–160
KiM (2019) Mobiliteitsbeeld 2019, Kennisinstituut voor Mobiliteitsbeleid, Den Haag, November 2019
KiM (2022) Mobiliteitsbeeld 2022, Kennisinstituut voor Mobiliteitsbeleid, Den Haag, November 2022.
Klimaatakkoord (2019) Klimaatakkoord, Den Haag, 28 juni 2019
Kurtuluş R, Çetin IB (2020) Analysis of modal shift potential towards intermodal transportation in short-distance inland container transport. Transp Policy 89:24–37
Min. IenW (2019) Goederenvervoeragenda. Agenda voor een robuust, efficient en duurzaam transportsysteem. Ministerie van Infrastructuur en Waterstaat, juli 2019, Den Haag
Nocera S, Cavallaro F, Irranca GO (2018) Options for reducing external costs from freight transport along the Brenner corridor. Eur Transp Res Rev 10:53. https://doi.org/10.1186/s12544-018-0323-7

Panteia (2016) Potentie multimodale continentale ladingstromen voor de Goederenvervoercorridors, Zoetermeer, 3 oktober 2016
Panteia (2019) Onderzoek modal shift potentie continentale ladingstromen via bovengemiddelde knooppunten, Samen werken aan Topcorridors, mei 2019
Panteia (2020a) Goederenvervoercorridor Zuid (ARA Corridor), Zoetermeer, 6 januari 2020a
PBL and CPB (2015) Nederland in 2030 en 2050: Twee referentiescenario's. Planbureau voor de Leefomgeving en Centraal Planbureau, Den Haag, 2015. PBL-publicatienummer: 1689
Pinchasik DR, Hovi IB, Mjosund CS, Gronland SE, Fridell E, Jerksjo M (2020) Crossing borders and expanding modal shift measures: effects on mode choice and emissions from freight transport in the Nordics. Sustainability 12:894. https://doi.org/10.3390/su12030894
Rondaij A, Fransen R, van Meijeren JC, Spreen JS (2020) $CO_2$-besparing ten gevolge van modal shift op de corridors Oost en Zuid in Nederland, Decamod effectrapportage, TNO 2020 R11941, TNO en Topsector Logistiek
TNO (2017) Modal shift van weg naar spoor. Potentie tot 2050 en effect op $CO_2$-uitstoot, TNO 2017 R10463, Dan Haag, 2017
Van Meerkerk J, Blomjous D, Nauta M, Geilenkirchen G, Hilbers H, Traa M (2020) Actualisatie invoer WLO autopark mobiliteitsmodellen 2020, Planbureau voor de Leefomgeving, Den Haag, 2020
Van Eck JR, Hilbers H, Blomjous D (2020) Actualisatie invoer mobiliteitsmodellen 2020, Planbureau voor de Leefomgeving, Den Haag, 2020
Van de Lande P, den Boer E, Wagter H, van den Berg R, van Essen H, van Rijn J, Spreen J, Outlook Hinterland and Continental Freight 2018, Topsector Logistics, July 2018
Vierth I, Sowa V, Cullinane K (2019) Evaluating the external costs of a modal shift from rail to sea: an application to Sweden's East coast container movements. Eur J Transp Infrastruct Res 19(1):60–76
Visser J, Francke J, Gordijn H. (2012) Multimodale achterlandknooppunten in Nederland. Kennisinstituut voor Mobiliteitsbeleid, Den Haag, juli 2012
Zhou Y, Vyas AD, Guo Z (2017) An evaluation of the potential for shifting of freight from truck to rail and its impacts on energy use and GHG emissions. Report. Argonne National Laboratory, Argonne, IL
Zimmer W, Schmied M (2008) Potentials for a modal shift from road to rail and ship—a methodological approach, ETX/ACC technical paper 2008/18, December 2008, European Topic Centre on Air and Climate Change

## Publisher's Note