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DECARBONISATION OF A HINTERLAND FREIGHT CORRIDOR FOR 2040

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Samenvatting

De transport sector is in Nederland de op een na hoogste sector qua emissie uitstoot, met 19% van het totale energieverbruik. Waar andere sectoren steeds duurzamer worden, blijkt de transportsector een van de moeilijkste sectoren zijn om te verduurzamen, ondanks veel onderzoeken in dit veld. Dit onderzoek heeft een lijst verzameld met potentiële uitstoot verminderende maatregelen en gecombineerd in een pakket om 80% CO_2 emissies te reduceren in 2040 voor de achterland corridor met hoog aandeel railvervoer tussen Rotterdam en Venlo. Door een literatuuronderzoek en interviews met expert is de lijst met 8 maatregelen samengesteld die zijn gebruikt in een normatief scenario. Na de berekeningen is het resultaat van 80% reductie van CO_2 emissies behaald, maar wel met een grote kanttekening. De reductie is sterk afhankelijk van een groot aanbod en overstap naar biobrandstoffen en het elektrificeren van de voertuigen voor alle modaliteiten. Dit vereist een hoge inzet van alle partijen in de sector met een intensieve samenwerking en mogelijk andere inrichting van de huidige logistieke keten. Hoewel het verbeteren van de logistieke efficientie niet hele grote impact heeft op het verduurzamen van de sector op de lange termijn, reduceert het wel de vraag naar primaire energiebronnen, en zorgt het er ook voor dat er minder vraag naar de schare biobrandstoffen en groene elektriciteit is.

Abstract

The transport sector is the second highest emitting sector in the Netherlands, with 19 % of the total energy consumption. Where other sectors are becoming more sustainable, the transport sector remains one of the most difficult to decarbonize, despite the many studies in this field. This research aims to gather a list of potential measures and combine them to reach an 80% reduction of CO_2 emissions in 2040 for the hinterland freight corridor of Rotterdam – Venlo which has a high rail freight intensity. Literature study and expert interviews established a list of potential measures. Using an iterative normative scenario design approach, a list of 8 potential measures with corresponding targets was drafted. After computation, a reduction of 80% is estimated for the corridor. The results show that for this particular corridor, the reduction depends greatly on the availability and adaptability of biodiesels and the electrification of vehicles and vessels. In contrast, measures aiming to improve the logistical efficiency do reduce the total energy required and could therefore alleviate challenges related to biodiesel availability and electrification, but have a smaller potential in reducing CO_2 emissions.

1. Introduction

In the past century, the total annual primary energy consumption has multiplied by almost ten times around the globe (Our World in Data, 2023). As the majority of this primary energy is produced by fossil fuels, the CO_2 emissions have also increased, during these years. In the Netherlands, about 19% of the energy is consumed by the mobility/transport sector (CBS, 2023), the second highest share after the industry sector. However, the transport sector is one of the most difficult sectors to decarbonize (McKinnon, 2018). This research studies the impact of measures on decarbonization towards 2040. First of all, the short-term reduction goals for 2030 are already determined in many sectors, as well as the long-term directions for 2050.

1.1. Scope

This research focuses on the long-distance Dutch Hinterland Freight Corridor 'Zuid-Oost' between Rotterdam and Venlo. Along the corridor, two main seaports are located in Rotterdam and Moerdijk. Therefore, transport between these two ports and the hinterland (Venlo and towards the German border at Venlo) is considered: both national and international transport. Along the corridor, three modalities are considered, road, rail and inland waterways transport. The pipeline network that is available between Rotterdam and Venlo is outside the scope of this research. Regarding the emissions, this study considers the Well – to – Wheel / Wake emissions.

1.2. Research Question

This research continues on the study performed by TNO on the decarbonization potential of the same corridor towards 2030. This study showed that with a lot of effort only half the reduction goal for 2030 would be reached (Rondaij et al., 2023). Expanding this approach to 2040 could lead to the similar conclusions. Therefore, an alternative approach for 2040 is executed in which a normative scenario approach should give a reduction of 80% of emissions on the corridor compared to 2014. This is leading to the following research question:

Which measures and innovations are needed to reach the emission reduction goals of 80% for 2040 in a normative scenario for the Rotterdam-Venlo freight corridor?

2. Methodology

In Figure 1, the approach to this iterative normative scenario design is visualized. The first step is to set the reduction target as described in the introduction of this paper. With the data analysis, the reference emissions will be determined. With the literature study and expert interviews, a list of potential mitigation measures can be constructed which will be combined in a consistent and coherent set of measures. At this point, the baseline or reference scenario for 2040 will be estimated with a Business–as-Usual forecast. Two alternative scenarios will be designed with a different set of emission reduction measures and by use of DeCaMod (TNO, 2020), the reduction will be computed and the estimated outcome of the scenarios will be compared to the reference scenario. If the reduction target is met, the process will stop, otherwise the measures and set of measures are adapted and the process will be executed again.

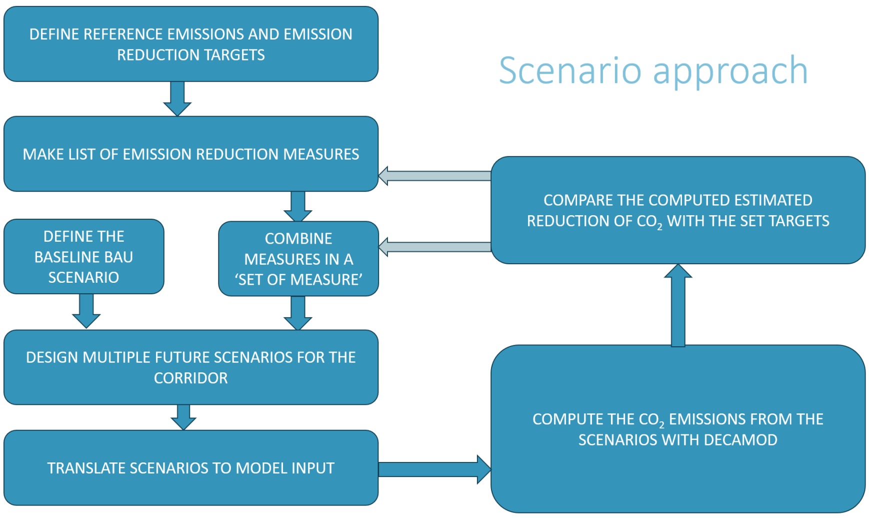

Figure 1. Normative scenario design approach

2.1. Literature Analysis

The literature analysis is based on the five decarbonization strategies by McKinnon (2018), which are: (1) reduce the freight demand, (2) shift to a more sustainable mode of transport, (3) better utilization of assets, (4) improve vehicle efficiency and (5) switch to another energy carrier. Papers are included if they state the potential of CO_2 emission reduction due to measures under the 5 categories listed above. The main focus of the literature analysis is on the reduction potential and the application potential of the discussed measures. Papers are preferably published after the book of McKinnon, therefore, after 2018.

2.2. Expert Interviews

In addition to the literature analysis, 11 expert in logistics were interviewed about potential measures and solutions for decarbonizing this Dutch corridor. The experts were asked about the implementation potential of a measure on the corridor, as well as the measures with the highest CO_2 reduction potential. The interviews were held in a semi-structured manner with the experts being asked a variety of questions and statements. The statements had to be answered on a scale of 1-5. The higher the number, the more the expert agreed with the statement.

2.3. BAU scenario

The data obtained contains transport data from 2014. Therefore, the reference year will be set to 2014. Then, for forecasting the transport demand in 2040, a Business-As-Usual (BAU) scenario will be designed based on standing policies. For this, the *Klimaat- en Energieverkenning* (KEV) (PBL, 2019) is used. This provided growth predictions for the transport on the corridor per OD-pair, modality and type of freight (NSTR). The BAU scenario will be used as a baseline to compare the normative scenario designs to, on which the measures will be applied.

2.4. Scenario Design

Designing the normative scenarios for 2040 is the main focus of this paper. These are traditionally used to support decision-making on uncertain futures (Van der Heijden, 1996). Although there is no specific definition, it is described rather as a narrative description of a hypothetical future than a prediction (Kishita et al., 2020). The narrative is then used to share ideas and images with the involved actors (Berkhout et al., 2002) . It is important to do this accurately, because designing the scenarios is the first step, but effectively implementing them in the real world can be very challenging (Kishita et al., 2016). The scenarios should fit some requirements as well, it should be consistent, but another important requirement is their plausibility (Amer et al., 2013). According to (Urueña, 2019), a scenario is plausible when an individual or collective agent (1) agrees with the initial (or current) state and the set of assumptions and (2) deems it reasonable that the narrative may lead to the final normative scenario. For this paper, two scenarios are designed named *Optimistic* and *Conservative*. In the optimistic scenario, more advanced adaptation of the implemented measures are applied, whereas the conservative scenario requires less drastic changes in operations compared to the optimistic scenario.

3. Literature study and Expert Interviews

A literature study combined with expert interviews resulted in a list of solutions divided into two categories. The first category focuses on improving the logistics operations, linked to the first three strategies of McKinnon (2018) and the second category focuses more on improving the technological aspects such as vehicle efficiency or change of energy carrier, linked to strategies four and five.

3.1. Logistical improvements

By improving the logistical operations, measures and solutions should be found that focus on transporting as much freight as possible in fewer vehicle kilometres, by improving the load factor of empty kilometres driven. The load factor can be evaluated by different factors (Ahmad et al., 2022). Amongst others, it can be restricted by weight (Ülkü, 2012) or volume (Santén, 2017). McKinnon (2018) listed seven reasons for inefficient transport regarding the load factor.

These reasons included: Logistical Trade-offs, lack of information, scheduling, dimensional incompatibility, lack of collaboration, traffic imbalances and regulations. According to multiple studies, (Abideen et al., 2023; van Lier et al., 2016) horizontal collaboration can tackle some of these listed reasons and improve the load factor as well as reduce cost (Abideen et al.,2023). According to the case study by van Lier et al. (2016), the share of trucks loaded with less than 60% capacity decreased from 43% to 36%. However, according to the literature review by Abideen et al. (2023), the two most cited limiting factors for horizontal collaboration are the trust between actors and the quality of information which is in line with the findings of (Pfoser et al., 2016).

Improving digitalization in the logistics sector can, according to the experts consulted, contribute to better collaboration, increased logistics efficiency and reduced CO_2 emissions. In the short-term, digital platforms can provide better insight into emissions as discussed by a study from(van Meijeren et al., 2024). On the longer term, more data sharing can lead to more innovative concepts such as Synchromodality and Physical Internet. Synchromodality can induce a modal shift and therefore reduce emissions (SOURCE: Lemmens et al, 2019; Zhang & Pel 2016) and it is very suitable for long-distance corridors (AMBRA et al. 2019). Physical Internet can contribute in reducing carbon emissions by optimizing logistical processes (Peng et al., 2020; Kurtulus & Ismail, 2020) and improving logistics efficiency by using modular uniform containers (π-containers (Montreuil, 2011)).

Another logistical improvement is the introduction of High Capacity Vehicles (referred to as Super EcoCombi's), which can transport twice the amount of TEU as a regular truck. Therefore it can transport twice the freight of regular trucks in half the vehicle kilometres (vkm) (BCI & CE Delft,

2020). According to (CLOSER, 2017), these trucks do require more energy per vkm, which is an increase of 30% compared to regular trucks. All in all, multiple case studies show promising results with significant emission reductions (Cider & Ranäng, 2014; Larrodé & Muerza, 2021).
Lastly, according to the experts and literature, decreasing the speed of vessels can be an important factor in the reduction of energy required as this follows the cubic law of design speed and operational speed (Corbett et al., 2009). Sailing at optimal speed can reduce emissions by 28% according to (Lindstad et al., 2011). However, lowering the speed can cause disruptions in the operations, causing the increase of vessels required. According to Corbett et al. (2009), this can still lead to an overall decrease in emissions.

3.2. Measures focused on Technological improvements

Strategies 4&5 of McKinnon (2018) focus more on the emissions from the characteristics of the engines and energy carriers. Interesting values for literature are the vehicle efficiency (MJ/vkm) and emissions per energy unit (kgCO_2/MJ) for both Tank-to-Wheel (TTW) and Well-to-Tank (WTT) emissions. From the expert interviews, a probable development regarding alternative fuels and energy carriers is derived. In the short term, a transition to bio-diesels is most likely, whereas in the longer term, the transition to more electric engines is considered. First therefore, the biodiesels are discussed. The most well-known biodiesels are HVO (*Hydrotreated Vegetable Oil)* and FAME (*Fatty Acid Methyl Ester)*. When biodiesels are used, the vehicle efficiency changes slightly, but not significantly according to (Bortel et al., 2019). For these biodiesels, only WTT emissions are considered as the CO_2 that is emitted comes from a short-term cycle process, adding no additional emissions to the atmosphere (Gustafsson et al., 2020; Esposito, 2020). According to Esposito (2020), the WTT emissions from HVO can be reduced with 51% compared to regular diesel. According to (CO_2Emissiefactoren, 2015) the reduction for FAME compared to diesel is also about 50%. According to the experts, the increase in electric vehicles is expected to be higher than in hydrogen vehicles after 2030.
With regards to the energy carrier efficiency, then can be concluded that the electric engines require less primary energy per vkm than regular diesel. For trucks, the primary energy demand decreases by about 65%, for trains, the decrease is about 63% and lastly for barges about 59% (Breuer, et al., 2022). For electric engines, the TTW emissions are considered to be 0. However, the WTT emissions are depending on the share of green electricity that is available. For the barge modality, the experts state that there is a higher electrification potential for intermodal (container) transport compared to bulk. Alternative solutions were also brought up or discussed with the experts. One of the alternatives is to place solar panels on trailers of trucks. These panels, in combination with a battery package to store the energy and regenerative braking on the trailers could reduce the fuel consumption (and therefore emissions) by 5-9% (Kutter et al., 2021). Lastly, studies have been done towards the use of big sails and kites on ships. This could lead to savings (depending on the wind) between 1 and 36%

(Psaraftis, 2015; Schlaak et al., 2009). However, questions could be raised about the implementation of these sails and kites for Inland Waterways Transportation on the corridor.

4. Data Analysis and Baseline reference

For this study, the reference emissions to define the 80% reduction are determined from the data analysis of the 2014 BasGoed (*Basisbestanden Goederenvervoer*). After that, the forecast is made for the BAU scenario for 2040, which will be the baseline of the scenario analysis.

4.1. Reference year 2014

To define the reference emissions, the first box in Figure 1, the data has to be analysed. From this analysis, some deviating aspects occurred compared to other hinterland freight transport corridors. When only transport between national origin destinations pairs (so no cross-border transport) is considered, the modal split looks very plausible. It shows an high share of transport assigned to the barge modality, as well as the major share of containers being transported by barge transport. The rail freight transport consists mostly of intermodal (container) transport.

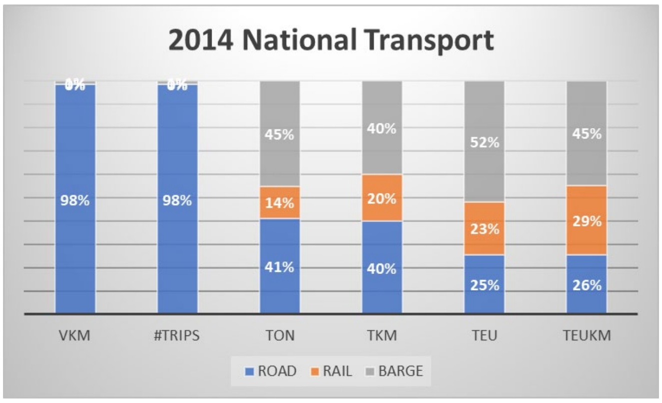

Figure 2. KPI of the National transport in 2014

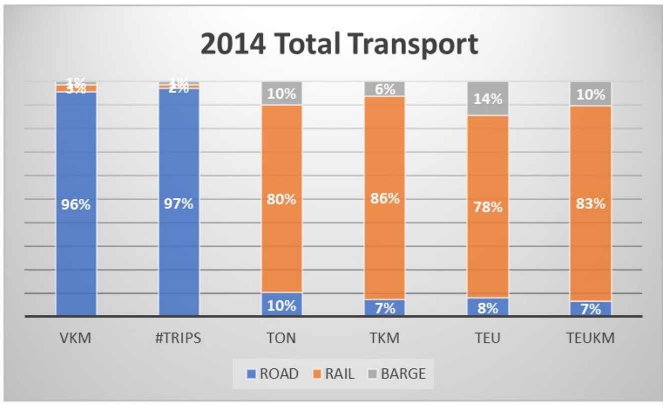

Figure 3. KPI of the total transport in 2014

However, when the international transport on the corridor is also considered, the KPIs show a very different modal split. The highest share of transport is international rail freight. This can be explained since there is no international water crossing to Germany around Venlo, so for that modality, there is no international transport considered. For road freight transport, from Moerdijk and Rotterdam towards Europe, alternative routes are likely considered instead of Venlo, decreasing the share of transport from these destinations. Therefore, for this particular freight corridor with destination pairs, the share of rail freight is very high as shown in Figure 3.

Rail freight generally produces less emissions than the alternative modalities. Therefore this also has an impact on the reference emissions and reduction goal. According to the experts, about 20% of the longhaul freight trains have diesel engines, whereas the other 80% use electric engines. For the corridor, the total distance is considered to be a highway, as the first and last mile off the highway are a minor part of the trip. Lastly, the energy requirements for barges are based on the NEA database (NEA). Other emission factors for the modalities are obtained from (CO2Emissiefactoren, 2015; Rolim et al., 2012; TNO, 2017). This resulted in a total Well-to-Wheel emissions of *66.1 kton* CO_2. From this, about 52 kton is due to TTW emissions and 14 kton due to the WTT. As the reduction goal of this study was set to 80%, the total allowed emissions on the corridor is equal to $0.2 * 66.1 = \mathbf{13.2}$ *kton* CO_2.

4.2. BAU scenario 2040

Now, the reference emissions, reduction target and a list of potential emission reductions are constructed. Therefore the baseline BAU scenario has to be designed. For this BAU scenario, the expected growth of the freight on the corridor has to be determined. Changes in emission factors or energy carriers are not taken into consideration for this BAU scenario. The demand growth is based on the *KEV* (PBL, 2019). These growth figures are then computed by (Signifcance, 2019), based on The WLO studies by (CPB & PBL, 2015), depending on OD-pair, modality and type of freight.

This forecast then provided a new modal split for both the national and the international freight. Figure 4 shows the new national situation of the KPIs. Here the share of transported tons increased from 14 to 31%. This can be explained by two factors. Firstly, there has been a shift of commodities of freight types over the years, with an increased demand of intermodal transport and a decrease of bulk transport. Secondly, a small share of road freight transport is expected to shift to rail freight transport towards 2040. The commodity change also has an impact on the barge modality. The total amount of tons transported has decreased, whereas the total distance covered has increased. Intermodal transport generally weighs less than bulk, therefore more kilometres are needed to transport the same amount of tons.

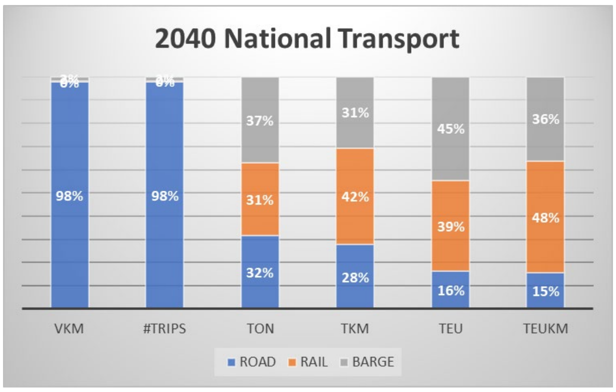

Figure 4. KPI of the National transport in 2040

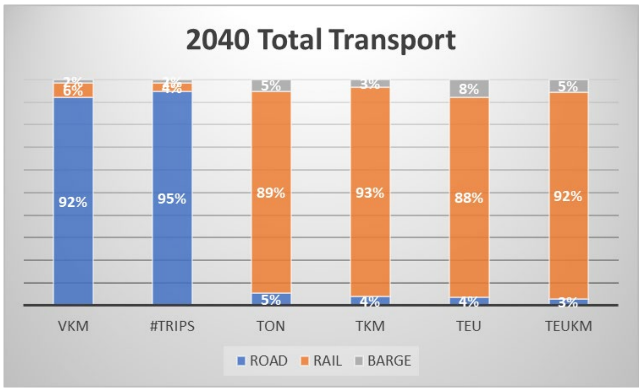

Figure 5. KPI of the National transport in 2040

The high share of rail freight transport as discussed in Section 4.1 becomes more crucial as the growth factors for international transport are estimated to be 3-4% per year. The average growth factor is much lower, at 1.1%. Therefore, the already high share of rail transport becomes even higher as shown in Figure 5. This can have a big impact on the scenarios, therefore the influence of the high rail share will be tested in the Sensitivity Analysis.

With the same emissions factors used as in 4.1, the total WTW emissions for this BAU scenario have increased to 71.4 *kton* CO_2. This is an increase of 8.8% compared to 2014.

5. Normative Scenario Design

With the BAU scenario determined, the next step is to define the 'set of measures' in the scenarios. For the start of the normative scenario design, the solutions discussed with literature and experts are placed in a decision matrix, shown in Figure 6, based on current assumptions about the importance of the solutions regarding the reduction of CO_2 emissions and the uncertainty that a solution will be developed or used. The matrix consists of four quadrants and distinguishes between solutions focused on the logistical operations and technological developments.

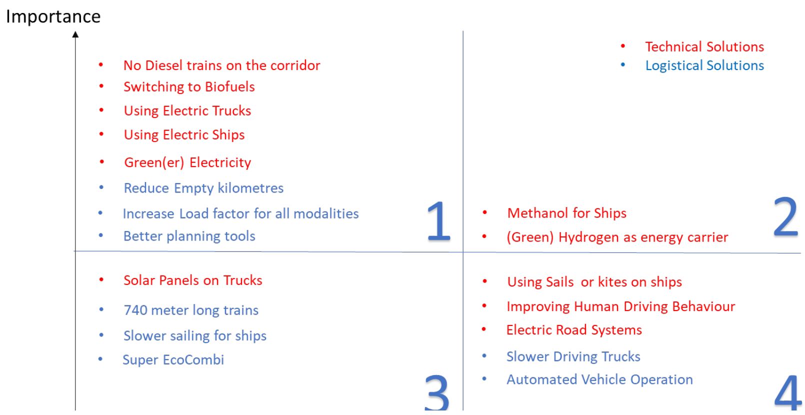

Figure 6. Decision Matrix of the proposed solutions, based on (van Binsbergen, 2024)

The determination of which solution is placed in which quadrant is based on the expert interviews. One should note that this is based on current views which might shift over the years with more and new research towards relatively unpractised solutions. For this study, the solutions assumed to be the least uncertain (quadrants 1 & 3) are used in the normative scenario designs. As explained in Figure 1, the approach is an iterative process. Three iterations are performed, in the first iteration, only the technological improvements are considered, in the second iteration the logistical operation improvements are included. In the last iteration, the effect of the measures and solution is increased, and the share of biodiesel is increased to the point that an 80% reduction is reached. As mentioned, two scenarios are designed, a more optimistic, adaptive scenario with more drastic targets, and a conservative scenario which focuses more on the less drastic changes.

5.1. Final Set of measures

The final set of measures is determined after the third iteration. The package of measures consists of a total of eight measures. The effects of the first three measures are combined as they have an impact on similar parameters that will be explained in Section 6. These measures are M1*: (Introducing a* CO_2 *tax),* M2*: (Truck Kilometre Charge)* and M3: (*Facilitation and integration of Digital Platforms / Systems*). The first two measures introduce a monetary penalty which will be increased every year to compensate depending on the emission of the total value of the penalty for the emitted CO_2 and kilometres driven. This makes the more sustainable alternatives (biodiesels, electrification) more attractive. To furthermore reduce the total kilometres driven or the empty vehicle kilometres, more collaboration is required which can be obtained with Digital Platforms to improve scheduling, data sharing and better insights. This may increase the load factor, reducing the total kilometres driven. It should be noted that the increase in the load factor also results in a slight increase in energy required per driven kilometre.

The first two measures are mainly focused on road and barge freight transport. For rail, a more strict measure will be applied M4: *(Ban of diesel trains on the corridor)*. As mentioned, about 20% of the trains still runs on diesel engines, therefore these will be banned from the corridor. Due to this electrification, the emissions for electric transport will depend on the share of green electricity. M5: (*Installation of renewable electricity sources*) has to ensure that the majority of generated and consumed electricity comes from low-carbon or emissions-free sources.

The last three measures are each focused on a specific modality. Firstly, M6: (*Legalise the Super EcoCombi*) is proposed. The potential for these trucks is higher on these hinterland corridors with a high share of intermodal transport. By legalizing these trucks, and increasing the maximum weight, the total vehicle kilometres can be reduced, at the cost of a small increase of energy required per km. For trains, the regulations state that more trains should reach lengths of 740 meters (Council of the EU, 2024). However, the current infrastructure is not equipped for large amounts of these trains. Therefore M7: (*Subsidies essential renovations and upgrades to the railways for more than 740 metres long trains*). Over time, the average length of trains can therefore increase. This measure is applied for intermodal transport as bulk freight transport is more likely to be limited by weight (ProRail, 2024).

The last measure is aimed at improving the barge modality. Literature showed that sailing at optimal speed reduces emissions compared to sailing at design speed. Therefore M8: (*Dynamic speed limit on the river)* is introduced, setting an dynamic speed limit depending on the design speed of the vessel.

Furthermore, next to the measures introduced, a gradual increase in vehicle efficiency is taken into consideration between 2014 and 2024. Thereafter, it is assumed to stagnate as the focus of OEMs shifts towards the Battery Electric Vehicles (BEV).

6. Model Formulation

After designing the set of measures into scenarios, the scenarios need to be translated to model input and then evaluated with DeCaMod (TNO, 2020). This section describes the way the emissions are computed.

Figure 7 presents a simplified flow chart of the computation of the CO_2 emissions. First of all, it starts with the amount of freight that needs to be transported. Then due to the measures improving the logistics efficiency, the new variable *vkm/ton* is used to transport the total vehicle kilometres needed to transport the amount of freight. The next step is to compute the total required energy. This depends on multiple factors amongst other: the load factor, speed and type of vehicle and energy carrier. Lastly, based on the energy requirements, the total emissions are computed both for TTW and WTT. This is based on the energy carrier that is used whether regular diesel or biodiesel is used.

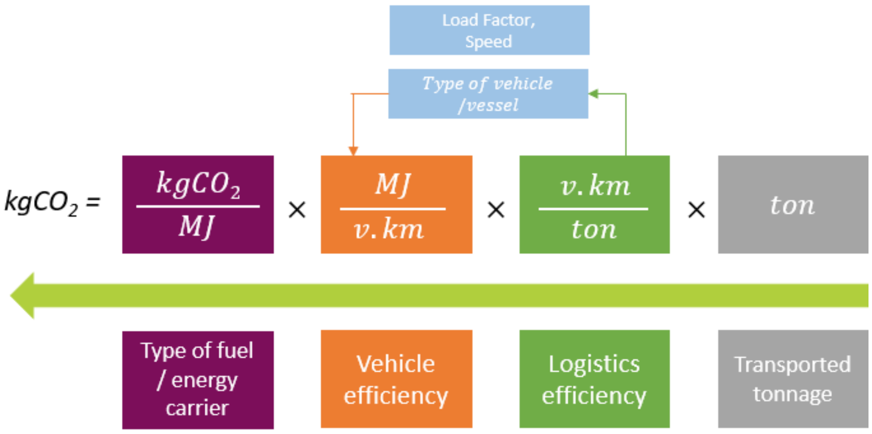

Figure 7. Simplified flowchart of DeCaMod (TNO, 2020)

The model takes three sets into consideration shown in Table 2. First of all, the set of years in the study: $I = \{2014, 2015, \ldots, 2040\}$. Secondly, three modes are considered in this research, therefore the sets of modalities is: $M = \{Road, Rail, Barge\}$. Lastly, the set of container transport: $C = \{0,1\}$, in which 0 is no container transport and 1 means container transport.

Table 2. Indices and Sets used in the model

Indices	Description	Set
i	Years that are considered in the study	$i \in I$
m	Modalities used on the corridor	$m \in M$
c	Binary value whether container transport is used	$c \in C$

Corresponding with Figure 7, the adjustable parameters are shown in Table 3

Table 3. Parameters used in the model

Parameter	Definition	Unit
$ton_{i,c,m}$	Ton transported on the corridor for year i for mode m with or without containers	$[10^3 kg]$
$vkm/ton_{i,c,m}$	The vkm needed to transport a unit of freight for year i with mode m with or without containers	$[km/10^3 kg]$
$MJ/vkm_{i,m}$	The used MJ per vehicle kilometer travelled for year i for mode m	[MJ/km]
$kgCO_2[TTW]/MJ_{i,m}$	Kg of CO_2 emitted per MJ energy for year i for mode m (TTW)	[kg/MJ]
$kgCO_2[WTT]/MJ_{i,m}$	Kg of CO_2 emitted per MJ energy for year i for mode m (WTT)	[kg/MJ]

These adjustable parameters are adapted for each year and modality depending on the reduction value determined by the measures. This reduction is the multiplication of the total effect in 2040 of a measure with the share of the year i: S_i as shown in Equation (1).

$$reduction_i = effect \cdot S_i \quad \forall i \in I \tag{1}$$

The share of the effect of the year (i) is depending whether the implementation of the measure follows a more s-curve path according to the Boltzmann Equation (Equation (2)) or a linear path (Equation (3)).

$$S_i = \begin{cases} 0, & if\ 2014 \le i \le i_{start} \\ \dfrac{1}{1 + \exp\left(\dfrac{i - i_{mid}}{Slope}\right)}, & if\ i_{start} \le i \le i_{end} \\ 1, & if\ i_{end} \le i \le 2040 \end{cases} \tag{2}$$

$$S_i = \begin{cases} 0, & if\ 2014 \le i \le i_{start} \\ \dfrac{i - i_{start}}{i_{end} - i_{start}}, & if\ i_{start} \le i \le i_{end} \\ 1, & if\ i_{end} \le i \le 2040 \end{cases} \tag{3}$$

The updated values of the adjustable parameters can then be computed with Equation (4), with as example using the $MJ/vkm_{i,m}$ parameter.

$$MJ/vkm_{i,m} = (1 - reduction_i) \cdot MJ/vkm_{i,m} \quad \forall i \in I, m \in M \tag{4}$$

Equations (5-9) show the computations of the newly computed KPIs in the following order

$$vkm_{i,c,m} = vkm/ton_{i,c,m} \cdot ton_{i,c,m} \ \ \forall i \in I, m \in M \tag{5}$$

$$MJ_{i,m} = MJ/vkm_{i,m} \cdot \sum\nolimits_{c \in C} vkm_{i,m,c} \quad \forall i \in I, m \in M \tag{6}$$

$$TTW_{i,m} = \frac{kgCO_2[TTW]/MJ_{i,m} \cdot MJ_{i.m}}{1000} \quad \forall i \in I, m \in M \tag{7}$$

$$WTT_{i,m} = \frac{kgCO_2[WTT]/MJ_{i,m} \cdot MJ_{i.m}}{1000} \quad \forall i \in I, m \in M \tag{8}$$

$$WTW_{i,m} = TTW_{i,m} + WTT_{i,m} \ \forall\ i \in I, m \in M \tag{9}$$

Then for each year, the KPIs can be computed for all the KPIs above, following the example of Equation (10), except for the vehicle kilometres in Equation (11), which has an additional set for summation.

$$MJ_i = \sum_{m \in M} MJ_{i,m} \quad \forall\, i \in I \tag{10}$$

$$vkm_i = \sum_{m \in M} \sum_{c \in C} vkm_{i,m,c} \quad \forall\, i \in I \tag{11}$$

Lastly, the total cumulative emissions on the corridor from 2014 to 2040 can be computed with Equation (12):

$$WTW = \sum_{i \in I} \sum_{m \in M} WTW_{i,m} \tag{12}$$

Table 4 shows an overview of the output parameters from the equations above.

Table 4. Output parameters of the model

Output	Definition	Unit
$vkm_{i,m}$	The amount of vehicle kilometres for year i in mode m	[km]
vkm_i	The amount of vehicle kilometres for year i	[km]
$MJ_{i,m}$	MJ of energy that is required for transportation for year i for mode m	[MJ]
$TTW_{i,m}$	Total emitted ton of CO_2 (TTW) in year i for mode m	[ton]
$WTT_{i,m}$	Total emitted ton of CO_2 (WTT) in year i for mode m	[ton]
$WTW_{i,m}$	Total emitted ton of CO_2 (WTW) in year i for mode m	[ton]
MJ_i	Total required energy for year i	[MJ]
TTW_i	Total emitted tons of CO_2 (TTW) in year i	[ton]
WTT_i	Total emitted tons of CO_2 (WTT) in year i	[ton]
WTW_i	Total emitted tons of CO_2 (WTW) in year i	[ton]
WTW	Total emitted tons of CO_2 (WTW) between 2014 and 2040	[ton]

7. Results

In Figure 8, the results per iteration are visualized. The measures aimed at technological developments from iteration 1 resulted in a reduction of 66% and 59% of CO_2 emissions compared to 2014. By adding the measures aiming to improve logistical efficiency, the reduction increased to 71% and 63% for the optimistic and conservative scenarios respectively. Lastly, in the third and final iteration, both scenarios reached a reduction of more than 80%, obtaining the only normative scenarios as described in Section 5.

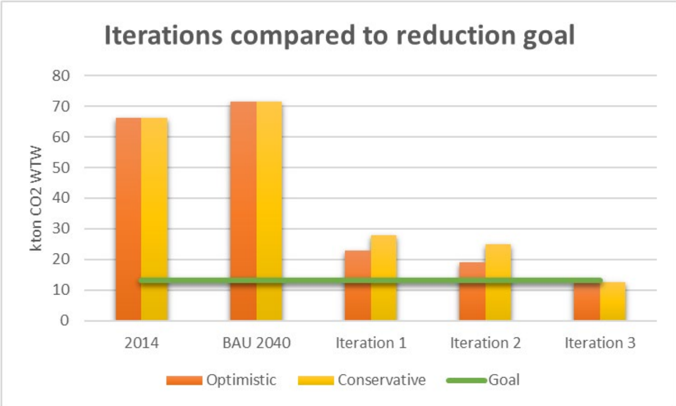

Figure 8. Results of the iterations

For the third and final iteration, the measures and corresponding targets for the solutions are stated in Appendix A in Table A.1. as described in Section 5. The distinction between the optimistic and conservative scenarios can be seen. The optimistic scenario has a higher adaptability of logistical measures, and the conservative scenario focuses more on electrification and biodiesels.

In Figure 9, the emissions are shown over time for the baseline, optimistic and conservative scenarios. Despite the difference in adaptation of measures, it can be seen that the decarbonization of the corridor follows a similar curve. It can be seen that initially, the optimistic scenario adapts quicker, with more reduced emissions at the beginning. Splitting up the emissions in TTW and WTT emissions, a difference can also be seen. The conservative scenario performs better in regards to TTW due to the high share of alternative fuels and electrification. With regards to WTT, the optimistic scenario performs better, as this scenario overall required less primary energy due to the higher level of logistical efficiency, as well as a higher share of green electricity. The results split in TTW and WTW emissions are shown in Figure B.1 and B.2 in Appendix B.

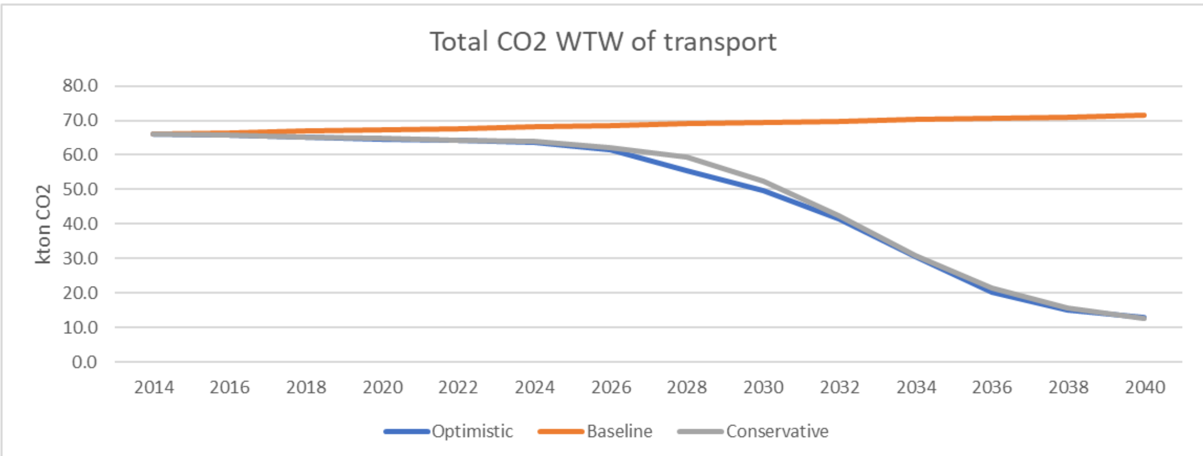

Figure 9. Well-to-Wheel emissions on the corridor between 2014 and 2040

7.1. Sensitivity Analysis

As the results are based on some assumptions made, a sensitivity analysis is performed on some of the more impactful parameters. Considered are the following analyses: dependency on green electricity, the forecasted transport, the high share of rail and the use of measures that either only improve technological development or logistical efficiency. In Table 5, the results of the sensitivity analysis are shown. It shows the reduction of emissions on the corridor with the current measures stating whether adaptation of targets is necessary.

Table 5. Results Sensitivity Analysis

Analysis	Reduction Optimistic scenario	Reduction Conservative Scenario
50% of all electricity is green	77%	78%
WLO high as BAU scenario	76%	76%
Decreased share of rail	79.5%	80.1%
Only Technological Measures	76%	78%
Only Logistical Measures	21%	12%

The results show that the high share of rail only has a small impact of the reduction on the corridor. Lowering the share of green electricity, using another BAU scenario or ignoring improving logistical efficiency required all additional adaptation to the targets to reach the 80% of emission reduction on the corridor. It was not plausible to reach the required reduction of emissions in the case of only using measures to improve logistical efficiency,

7.2. Implementation challenges

The study states what the outcome of the measures has to be to reach the reduction target on the corridor. It should be duly noted that challenges and barriers have to be overcome. The findings of this study state that the main challenges are the large-scale production, availability and price of bio-diesels as these diesels will have the highest impact on the decarbonization towards 2040. Furthermore, a large share of the fleet of trucks, trains and vessels will run on electricity. Except for trains, the charging infrastructure has to be developed and implemented. This is challenging as the corridor is situated in an area with a highly congested electricity network. Expansions on the electricity grid in these high quantities is not possible at the moment. Regarding the digitalization, restructuring of the supply chains is essential to reduce emissions. This requires more collaboration and flexibility towards planning and choice of modality. Lastly, some infrastructure elements for roads, railways and bridges on the corridor are nearing their end of life. For successful implementation of the measures, and prevention of disruption in the systems, the infrastructure maintenance and renovation should have a high priority.

8. Discussion

Within this study, it was inevitable to make assumptions that (could) impact the results. Therefore, some of these assumptions are discussed in this chapter, as well as a reflection on the results.

8.1. Input

The limitation of this study is found in the relatively old data set from 2014 on the transport volumes and freight characteristics on the corridor. The ten years between this dataset and this study give a higher uncertainty that the freight volumes have changed due to unforeseen circumstances. The effect of the COVID-19 pandemic, which is not considered in this study, is assumed to have recovered before 2040. Furthermore, the reduction target of this study significantly influenced the entire study. Based on the rationale of this study, the reduction target was set at 80%. It is important to note that another person conducting this study can opt for another target as the guidelines and directives per modality are not clear and can lead to multiple interpretations.

Lastly, in the expert interviews, the issue of disruptions for the barge modality regarding low water tides and staff shortages is mentioned. These disruptions are not considered, but probably will have an impact on the whole corridor.

8.2. Results

With the measures proposed in this study, the 80% reduction target is reached. It should be considered that this study focused on a hinterland freight corridor with an uncommonly high share of rail transport, also due to the high expected shift towards rail freight transportation. If this shift is not obtained in the future, the reduction targets will probably not be met, as rail freight transportation is more sustainable than road and barge freight transport. Another advantage of this corridor is the high freight volume along the corridor. This makes the corridor better suited for groupage and load consolidation. On freight routes not bound to a corridor, the reduction potential would be lower as these opportunities will be less available. Lastly, the rebound effects are not considered, therefore the impacts are yet unknown. The increased efficiency of the corridor may make transport less expensive and more attractive, resulting in more transportation and therefore more emissions.

9. Conclusion

To conclude, this study has provided a set of measures based on literature and experts findings that is estimated to achieve the reduction target of 80% CO_2 emissions on the hinterland freight corridor between Rotterdam and Venlo for 2040. The estimations computed with the model show that the corridor has a high dependency on biodiesels and electrification. Due to the high rail freight transport on this corridor, the impact of emission reduction due to improved logistical operations was limited. However, these improvements did reduce the demand of primary energy, resulting in lower demand for the limited availability of biodiesels and green electricity. Both scenarios showed that 80% reduction is in reach with the set of measure that this study proposes. The sensitivity analysis showed that depending on the outcome of certain assumptions, additional targets are necessary. Nevertheless, this study provides policymakers with better insights into effective measures and targets for the decarbonization of the transport sector. This study therefore has shown, that it is indeed possible to reduce the emissions with 80%, but it is only achievable if the discussed challenges are overcome and with extensive collaboration between all the involved parties within the transport sector in the Netherlands. It is very important to start with the implementation as soon as possible.

Based on, or during this study, some suggestions for further research came to light. First of all, reduction of freight demand, the first strategy of McKinnon (2018), is not discussed in this paper due to the lack of literature. However, reducing the freight demand could be very important in the reduction of CO_2 emissions on the corridors, as was concluded from the expert interviews. Further research could provide insights and methods to disconnect the freight demand from economic growth. Then measures can be researched to reduce the freight demand.

A follow-up study on the economic impacts of the measures proposed in this scenario also contributes to the feasibility of the measures. This research for example can be focused what the emission tax should be to achieve the goals that were set for the measures. Furthermore, a study can show how the decarbonisation of the barge modality can be subsidised to ensure that the required substitution of electric ships is feasible.

Lastly, a lot of studies, like this one, mention a certain demand for bio-diesels or other biofuels. However, research about the accurate production potential of bio-diesels is lacking.

This could provide additional accuracy to the results of this study. If the outcome of such a study shows that the increased demand for bio-diesel cannot be met, then other measures are needed to reduce the emissions on the corridor.

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Appendix A.

Table A.1. Overview of set of measures and set of targets per measure

Measure	Solutions in Optimistic Scenario	Solutions in Conservative Scenario
Truck Kilometer Charge CO_2 Tax	55% electric trucks 20%/12% electric vessels (container/ bulk) 45% share biodiesel in fuelmix for road 55% share of biodiesels in fuelmix barge	50% electric trucks 25%/12% electric vessels (container/ bulk) 55% share biodiesel in fuelmix for road 65% share of biodiesels in fuelmix barge
Truck Kilometer Charge CO_2 Tax Digital Systems	7% reduction empty kilometers 10%-point increase load factor Road 8%-point increase load factor Rail 8%-point increase load factor Barge	2% reduction empty kilometers 5%-point increase load factor Road 2%-point increase load factor Rail 2%-point increase load factor Barge
Ban of Diesel Trains	After 2030 no diesel trains	After 2035 no diesel trains
Renewable Energy	95% of all electricity is green	85% of all electricity is green
Super EcoCombi	25% of trucks in container, retail & distribution segment are SEC	23% of trucks in container, retail & distribution segment are SEC
Increase length trains	50m increase average length trains	25m increase average length trains
Speed limit on river	12% reduction of energy use	8% reduction of energy use

Appendix B

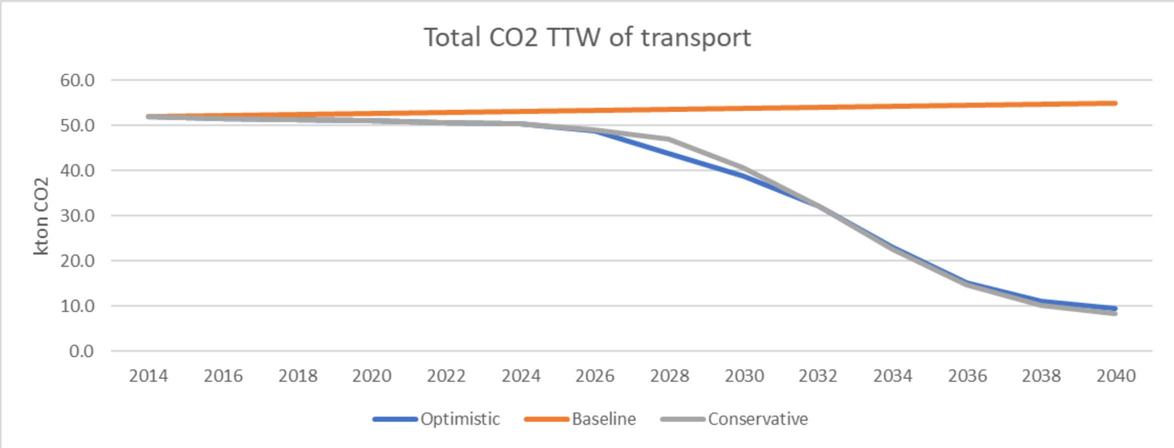

Figure B.1. Tank-to-Wheel emissions for the final iteration

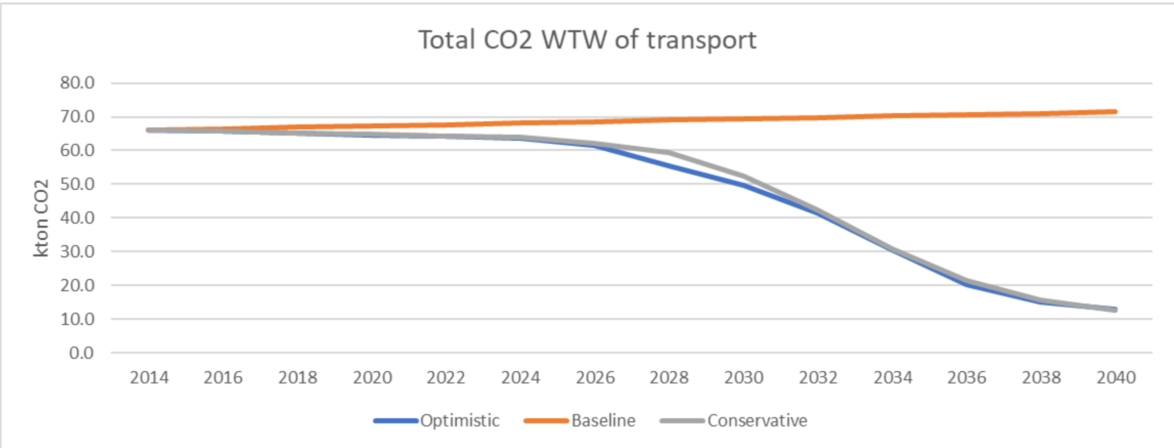

Figure B.2. Well-to-Tank emissions for the final iteration