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Sustainability Impacts of Mode Shift Scenarios on Major European Corridors

Working Paper 8 of the study Low-Carb-RFC - European Rail Freight Corridors going Carbon Neutral

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Abstract

Purpose: This publication is one of nine working papers compiled within the study "Low Carbon Rail Freight Corridors for Europe" (LowCarb-RFC). The LowCarb-RFC study concentrates on ways for de-carbonising long-distance freight transport along major European corridors as this sector is among the most steadily growing sources of greenhouse gas emissions in Europe, and which is most difficult to address by renewable energies and other standard climate mitigation measures in transport. This paper starts by elaborating an appropriate impacts assessment scheme, which is then applied to the transport model results for the LowCarb-RFC scenarios Pro Rail and Pro Road.

Results: Comparing the single-mode improvements of rail in the Pro Rail scenario and the decarbonisation of HGVs in the Pro Road case, the road scenarios get closer to a deep cut in GHG emissions. The explanation is that in both road scenarios an electrification of the motorways is foreseen, while the rail improvements are not accompanied by electrification of motorways. Although rail performs better than road and barge transport in terms of GHG emissions, physical and economic limits to mode shift prevent the railways from catering the lion's share of freight movements. Since by 2050 energy efficiency of railways will anyway approach an optimum, improvements to the freight sector's carbon footprint can only be undertaken for road and inland water transports. Options for bringing down road-based GHG emissions include the sector's electrification through overhead wires, batteries or synthetic fuels.

Conclusions: A combi scenario for 2050 using the Pro Rail scenario and 50% / 100% electrification of motorways was calculated. A 50% electrification would bring the Pro Rail scenario down to the level of Pro Road, a 100% electrification would reduce external costs to an even lower level than Pro Road. We can thus conclude that efforts on all sectors to reduce GHG emissions are of utmost importance and have to be implemented immediately as we seem to greatly fail the ambitious mitigation targets set in the past years.

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Abbreviations

BAU	Business-as-Usual
BMUB	Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit
BMVI	Bundesministerium für Verkehr und digitale Infrastrukturen
BVWP	Bundesverkehrswegeplan
CH_4	Methane
CO_2	Carbon dioxide
CO_2eq	CO_2 equivalents
DeStatis	Statistisches Bundesamt (Federal Statistical Office, Germany)
EBD	Environmental burden of disease
EC	European Commission
ECF	European Climate Foundation
ERTMS	European rail traffic management system
ETCS	European train control system
EU	European Union
GHG	Greenhouse gas
HBEFA	Handbuch für Emissionsfaktoren
HFC	Hydrofluorocarbon
HGV	Heavy Goods Vehicle
ICD	International Classification of Diseases
ICE	Internal combustion engine
IWT	Inland waterway transport
KS95	Klimaschutzszenario 95%
LDV	Light duty vehicle
LowCarb-RFC	Low Carbon Rail Freight Corridors for Europe
N_2O	Nitrous Oxide
NMVOC	Non-methane volatile organic compounds
NO_X	Nitrogen Oxides
NRMM	Non-road mobile machinery
NRW	North-Rhine-Westphalia
NSB	North-Sea-Baltic (corridor)
PM_{10}	Particulate Matter with a diameter up to 10 µm
$PM_{2.5}$	Particulate Matter with a diameter below 2.5 µm
RALP	Rhine-Alpine (corridor)
RFC	Rail freight corridor
SO_2	Sulphur Dioxide
tkm	Ton kilometre
TPR	Department of Transport and Regional Economics (at the University of Antwerp)
TRT	Trasporti e Territorio
UBA	Umweltbundesamt
UIC	International Union of Railways
vkm	Vehicle kilometre
WHO	World Health Organisation

1 Introduction

1.1 Context: The LowCarb-RFC project

This publication is one of nine working papers compiled within the study "Low Carbon Rail Freight Corridors for Europe" (LowCarb-RFC). The Study is co-funded by the Mercator-Foundation and the European Climate Fund (ECF) over a three-year period from September 2015 to November 2018 and is carried out by the Fraunhofer Institutes for Systems and Innovation Research (ISI, Karlsruhe) and for Logistics and Material Flows (IML, Dortmund), INFRAS (Zurich), TPR at the University of Antwerp and M-FIVE GmbH (Karlsruhe).

The LowCarb-RFC study concentrates on long-distance freight transport along major European corridors as this sector is among the most steadily growing sources of greenhouse gas emissions in Europe, and which is most difficult to address by renewable energies and other standard climate mitigation measures in transport. Starting from the classical suite of approaches 'avoid, shift and improve', the LowCarb-RFC methodology concentrates on mode shift to rail and mitigation measures in all freight modes along the two major transport corridors crossing Germany: Rhine Alpine (RALP) from the Benelux countries to Northern Italy and North-Sea-Baltic (NSB) from Benelux via Poland to the Baltic States. Besides major European strategies, the project concentrates on the implications for transport policy at the intersection of these two corridors, which is the German Federal State of North-Rhine-Westphalia (NRW). The project focuses on rail as a readily available alternative to carry large quantities of goods along busy routes by electric power, and thus potentially in a carbon neutral way. Within this setting, the project pursues three streams of investigation:

- **Stream 1: European Scenarios and Impacts**. For rail, road and waterway transport along the two corridors, cost and quality, scenarios are established and their impact on modal split, investment needs and sustainability are modelled. This stream is the analytical core of the study and shall provide the basis for the subsequent analysis of pathways of interventions.
- **Stream 2: Railway Reforms and Institutional Change**. It picks up the slow pace of climate mitigation in the freight transport sector and asks the question how regulatory frameworks, company change management processes or new business models can accelerate them.
- **Stream 3: Case Study NRW**. This step eventually breaks down the transport scenarios and intervention pathways to the local conditions in NRW and looks at the implications for investments or de-investments in certain infrastructures, jobs, economic prosperity and the environment.

1.2 Purpose of this working paper

This working paper contributes to Stream 2 of the LowCarb-RFC project analysing selected sustainability indicators of two alternative development scenarios for road, rail and waterborne transport on major European freight corridors. The paper starts by elaborating an appropriate impacts assessment scheme which is then applied to the transport model results for the LowCarb-RFC scenarios Pro Rail (Doll and Köhler, 2018) and Pro Road (Schade and Mader, 2018). The paper concludes with an interpretation of the sustainability assessment results and a proposal how the methodology can be applied for the LowCarb-RFC Case Study North-Rhine-Westphalia.

2 Review of the LowCarb-RFC Scenarios

In the course of defining the LowCarb-RFC scenarios we have reviewed detailed cost items of road, rail, barge and intermodal transport with generalised, bulk and containerised cargo. For the cost categories infrastructure, vehicles, energy, labour and administration 2015 cost structures were analysed and forecasted towards 2030 and 2050. The forecasts are partly based on existing studies, e.g. by the PRIMES or the ASTRA system dynamics models, transport sector statements and on an in-depth literature review.

2.1 The LowCarb-RFC Business-as-Usual Case

Already in the **BAU scenario** we see considerable cost efficiency gains towards 2050 along the corridors, which are more expressed for rail (-18%) than for road (-13%) and for IWT (-8%). This assumption is based on current observations of successes in re-structuring the sector. The still available enormous efficiency gains of the railway market will partly be utilised by measures which have already been implemented today. This is public subsidies, market opening, digitalisation, asset and labour management or the concentration on core markets.

In the BAU scenario road transport will profit due to company mergers and the long-term independency from fossil fuels. While road freight rates are expected to decline by 17% towards 2050, the relative cost advantage of rail is still 26%.

2.2 The Pro Rail Scenario

The **Pro Rail** scenario is characterised by massive investments in rail capacity in form of new infrastructure, but more important in high capacity and flexible train control and communications systems like ETCS / ERTMS level 3. With advanced asset and demand management platforms train, wagon and container space are filled close to system saturation. By these measures rail costs per ton kilometre are expected to decline by 59% towards 2050 for general cargo.

Truck operations in the Pro Rail scenario are partly restricted and are subject to stricter social rules and much higher road charges. In total truck operating costs are expected to climb up by 27% in 2050 relative to 2015. By that the relative cost advantage of rail improves further to 81%.

- **Infrastructure** costs for rail are cut by half towards 2030 and decreased further towards 2050 by public subsidies and economies of scale. For trucks we assume a tripling of infrastructure charges to cross-subsidise rail and IWT investments according to the Swiss model.

- **Rolling stock** related costs in rail freight decline massively due to modular wagon concepts, declining empty headings, increased load rates, cross-border fleet management and longer productive life spans. Road haulage, in contrast, faces an increase in truck holding and operating costs due to stronger technical requirements and regulations.
- **Energy costs** show a less expressed development. Energy prices are expected to rise towards 2030 and then fall slightly as more renewables come available. The harsh efficiency programmes in rail let energy cost fall here by 35% in Pro Rail against 2015, while higher energy taxes in trucking cannot compensate for more efficiency of HGVs in the Pro Rail scenario.
- **Labour costs** decline sharply in the rail sector due to massive automation and digitalisation. In the road sector this is less the case as automation here is restricted by law in the Pro Rail scenario.
- **Administrative costs** are among the major burdens of today's railways. The simplification of regulations, cooperation and digitalisation let this burden shrink by 70% in rail freight, and by 20% in road haulage in the Pro Rail scenario against 2015.
- **Load factors** and occupancy rates of vehicles and infrastructures take a key role for the development of transport costs. Through new infrastructures, longer or shorter but high frequency trains and a unique high standard train control systems, network throughput may double. Modular waggons, a central consignment management and the cooperative marketing of load space may add another 50% to rail network capacity related to net ton throughput. .

The following table summarises the figures, including inland waterway transport. The values are averaged for a 300 km shipment of general cargo.

Table S1: Summary cost development by cost category and scenario

Cost category	Rail		Road		IWT	
	BAU	Pro Rail	BAU	Pro Rail	BAU	Pro Rail
Infrastructure	-20%	-75%	0%	+200%	0%	0%
Vehicle	-25%	-60%	+9%	+52%	0%	-60%
Energy	-12%	-35%	0%	+15%	-30%	-30%
Personnel	-42%	-68%	-20%	+10%	-30%	-30%
Administration	-25%	-70%	-20%	-20%	0%	0%
TOTAL	-18%	-59%	-13%	33%	-8%	-37%

Innovative technologies, new forms of organising rail businesses and capacity are indispensable for achieving these efficiency gains. These rely on a massive expansion of capacity and quality at the railways through new tracks, moving block train control, longer and / or faster trains and optimisation of waggon load space use. Investment costs may easily exceed 22 billion euros for the German network alone. Related to the 50 billion tkm of additional traffic attracted to rail this is 0.80 €-Ct./tkm or roughly twice the current track access charges. Thus, political commitment and additional efficiency measures are needed. Investment plans moreover need to take account of the growing public concern against new infrastructures and particularly of the noise disturbance from freight rail. Quickly advancing the silencing of rail freight through modern rolling stock, low noise infrastructures and noise barriers thus constitutes an indispensable element of rail capacity enlargement programmes.

2.3 The Pro Road Scenario

As long as energy prices for whatever propulsion system of lorries remain low, the development of demand is not likely to change significantly within the next years and decades. Logistics will continue introducing new tools to meet the demand of the transportation market for high frequency delivery in which rail cannot contribute much. The structure of goods can also be expected to continue to develop away from traditional rail formats. And if any unexpected changes occur, road haulage is much more likely to be able to quickly respond to new opportunities than rail is. Safer and less noisy and polluting lorries driving in platoons instead of overtaking each other with very low speed differences will contribute to more public acceptance in the coming years. Traffic information, platooning, driver assistance systems, mobile networks as well as connected, remotely driven and autonomous lorries will drive down operating costs and increase road haulage energy efficiency.

- Road haulage **load factors** are expected to slightly increase in all scenarios. In this scenario however, mostly road-bound hub-and-spoke networks, backhauling, integrated supply chains, automated freight matching and larger lorries are expected to improve vehicle utilisation more than in the other scenarios. Therefore, the load factor increases to 115% instead of 105% of today’s factors by 2030 in the other scenarios, and to 125% instead of 110% by 2050.
- **Infrastructure costs** in road haulage are expected to decrease to 80% by 2030 and to 60% by 2050. The decrease is deducted from the fact that in Germany road tolls are levied lower for cleaner lorries, which are therefore expected to quickly diffuse into the fleets. Furthermore, dynamic road tolling and automatic driving could further contribute to more vehicles driving at lower fares during the night.

- **Rolling stock** costs for road haulage are expected to increase to 110% by 2030. This is deducted from, the (partially forced) proliferation of new and expensive digital equipment, aerodynamic improvements and drivetrains. Remote diagnostics will however soon start to slow down this increase of costs. Between 2030 and 2050, these investments will pay out for the sector due to economies of scale and the long lifetime of electric drivetrains, reducing these costs back to 105% of the 2015 cost level.
- **Energy costs** for road haulage are expected to fall to 90% by 2030 and to 74% by 2050 relative to 2015. This is due to the multiple effects of efficiency gains pushed by regulations as well as the use of alternative energy sources, v2x communication, driver assistance systems and automated driving. The purchase costs per energy unit is expected to fluctuate to some degree, but are not decisive for the per-km energy costs.
- **Personnel** costs for road haulage are expected to decrease to 70% by 2030 and to 30% by 2050 (whereas other studies[1] expect reductions by up to 90%). Because longer vehicles, automation and remote controlling decrease the need of staff and (the latter two) make the remaining tasks more attractive. They are expected to drop.
- **Administration** costs for road haulage are expected to drop to 85% to 2030 and to 60% by 2050. This is due to the expected fast development of digital administration tools and lower insurance rates due to safer vehicles.

Thus, without substantial policy action to improve the rail system and to promote the use of rail freight, it is much more likely for the pro road vision to become reality than for the pro rail vision.

1 Such as Bernhart and Roland Berger, 2016; e-mobil BW GmbH, 2015.

3 Assessment Methodology

3.1 General approach

3.1.1 Physical impacts and external costs

The movement of passengers and goods consumes energy by moving assets on built infrastructures. The impacts of the consequential interactions on people and nature are manifold and complex. They reach from the release of harmful substances into the atmosphere, water and soil to noise disturbance, crashes, the degradation of natural habitats and biodiversity, congestion and other impacts. All of these impacts can be quantified individually via their manifestation: tons of substances emitted, decibels of ambient noise or the costs of material damages and the number of injuries and death casualties following from accidents. These values are helpful to understand the nature of transport externalities and to check whether actual targets of thresholds are met.

Physical externalities, however, are difficult to compare to each other in order to achieve a single value of sustainability compliance. One way to narrow down the number of indicators is to trace the physical impacts down to end points of human well-being or environmental health. End points of human health are used by the method of the “environmental burden of disease” (EBD) applied by the world health organisation (WHO) to compare the harmfulness of different environmental stressors. The EBD looks for the ultimate health consequences of stressors like air pollution, noise exposure, smoking, alcohol abuse, etc. Typical end points are hypertension, ischemic heart diseases, cancer, sleep disturbance, psychological disorders, and all other entries of the International Classification of Diseases (ICD). These end points are assessed according to their severity between 0 (no impact) to 1 (close to death) by so-called “disability weights”. With these and the duration of the diseases and their spread, the total number of life years lost is computed. This is one single number across a multitude of impacts.

The EBD method is well applicable to all kinds of impacts on human health and quality of life, but it is not applicable to damages to our ecosystems. Here, eco inventories use concepts like eutrophication or acidification potentials. These are not directly comparable among each other and to life years lost computed by the EBD method.

A more general unique indicator to quantify the sustainability impacts of certain human activities is to quantify the impacts in monetary terms. This can be done by accounting for the actual damages caused (damage cost approach) or by estimating the costs of compensating for damages caused or for avoiding additional damages by reducing the environmental load below certain thresholds (avoidance cost approach). By all three methods we receive the social costs, i.e. the financial implications of the impacts imposed by transport on third parties and the environment.

Frequently the term “external costs” is used. This denotes social costs minus payments by the users, i.e. “internalised” social costs. This concept is relevant for pricing and taxation issues where “missing” internalisation contributions are to be identified. In this working paper we are interested in the damage caused by transport and thus stick to the more simple definition of social costs.

In this paper we use two of the three options presented above:

- Development of physical impacts to illustrate the magnitude of transport externalities.
- Social costs to compare impact categories and to receive a single sustainability indicator across all effects.

The type of impacts and their physical manifestation are described briefly in turn, and are elaborated in more detail in the specific section.

3.1.2 Components of social effects

In the introduction to this chapter we have listed a broad set of impacts which transport may impose on society and the environment. For the purpose of this paper we select a subset of indicators which reflect the most relevant effects on the environment and on people inside and outside the transport system.

- **Climate change** constitutes the lead externality in this assessment and is expressed by the emission of carbon dioxide (CO_2). Other climate gases like methane (CH_4), nitrous oxide (N_2O) or hydrofluorocarbon (HFC) are considered indirectly by expressing emission factors in CO_2 equivalents (CO_2eq) where available.
- **Air pollution** expresses the emission of very different gases into the atmosphere. In this assessment nitrogen oxides (NO_X) and particulate matter with a diameter up to 10 µm (PM_{10}) and below 2.5 µm ($PM_{2.5}$) are considered. Other pollutants like sulphur dioxide (SO_2), non-methane volatile organic compounds (NMVOC) are disregarded due to their overall minor contribution to the social costs of air pollution in land transport. However, SO_2 and particles are a major problem in marine shipping and harbour locations.

- **Noise pollution** is measured by the number of people affected above certain target values.
- **Accidents** are assessed only to the extent to which human health or life is affected, i.e. through the number of injuries and death casualties caused by freight transport. Material damages are not accounted for as they are usually covered by liability and other insurances.

Other social costs discussed above are not quantified in this study. This includes the risks of nuclear power generation, impacts of infrastructures on nature, landscape, habitats and biodiversity or the visual intrusion of transport infrastructures to people. Impact and social cost estimates of these categories are extremely uncertain and their overall value compared to the classical social costs of transport is limited.

3.1.3 Data sources

Transport flows by 10 commodity types between NUTS-2 regions along the two corridors are taken from the European Commission's ETISplus database for 2015 and 2030. 2050 values are forecast using PRIMES model results. Details of the demand side are laid down in LowCarb-RFC Working Papers 1 (Doll et al., 2017) and 7 (van Hassel et al., 2018).

Table 1: Studies and data sources used

Source	**Usage**
Wietschel et al. (2017): Feasibility study for Determining the Potentials of Hybrid-Trolley-Trucks for BMVI	Energy consumption, greenhouse gas emissions and investment costs for the introduction of hyprid overhead-wire trucks on German motorways
Repenning et al. (2015): Climate Protection Scenario 2050 for BMUB	Forecast of emissions from electrical power production for 2030 and 2040 according to KS95 scenario. This scenario foresees a reduction of greenhouse gas emission of 95% by 2050.
Doll et al. (2015): LivingRail Scenarios to 2050	Development of external cost rates in European passenger and freight transport towards 2050
Korzhenevych et al. (2014): EU Handbook on External Costs, vol. 2	Update of the 2008 Handbook on the External Costs of Transport for the European Union
E3MLab (2014): PRIMES description and Möst et al. (2018): Reflex assessment	Forecast of energy consumption and emission factors from internal combustion engines by mode of transport for 2030 and 2040 by the PRIMES model
UBA (2012a): Methodology Convention Environmental Costs 2.0	Specific external costs for each emission (per ton), for accidents (per casualty) and noise (per tkm)

Van Essen et al. (2011): External Costs of Transport in Europe 2008	Emission factors for transport modes. The data for German transport emissions were used.
BASt (2009): PM emission measurements of trucks	Measurement of exhaust and non-exhaust particle emissions (PM) from heavy trucks on motorways
German office for Statistics (www.destatis.de)	Accident rates for HGV on German Motorways in casualties per Million vehicle kilometres
EUROSTAT (ec.europa.eu/eurostat/)	Development of accident rates 1990 -2015 in Europe, as basis for accident rate forecast to 2030 and 2050

Source: Fraunhofer ISI

For the purpose of this impact assessment the commodity structure is disregarded. With average load factors vehicle, movements are estimated as these are the cause of the social impacts of transport. The final transport flows underlying the sustainability assessment in this paper are summarised in Section 4.1.

Emission factors, cost values and other details by transport mode are compiled from recent studies and statistics. These are summarised in Table 1.

3.1.4 Main drivers of transport sustainability

Assessing long-term transport impacts are related to a number of uncertainties that can only be overcome by making assumptions about the future development. Presently, a large number of new technologies are cropping up, but it is not given that all of them will sustain in a future market environment. The following technologies are of mayor importance to the impact assessment:

- Electric propulsion in road and rail freight transport
- Growth of renewable energies
- Proliferation of information technologies in transport

3.1.5 Electric propulsion in road and rail freight transport

The switch from internal combustion engines (ICE) to electric vehicles, as depicted in Table 2 will have strong impacts on air pollution and climate change. According to EU requirements all railway lines in all scenarios and on all corridor branches will be fully electrified by 2050, although the speeds towards this situation are assumed to vary.

The introduction of new technologies for road freight transport will have strong impacts on the scenario's sustainability performance as in all cases a pathway towards carbon-neutral electricity generation is presumed. In road haulage electrification enters the transport sector by overhead-wire, battery electric and trolley-battery hybrid trucks. This will happen in market niches and test beds in the BAU and Pro Rail scenarios, while motorway electrification by overhead wires will be largely rolled out in the Pro Road case. Motorway electrification will progress faster along the highly developed RALP corridor than on the more disperse branches of the NSB route. The Mod Road scenario ranges somewhere between the degrees of electrification in the BAU and Pro Road cases.

Table 2: Share of vehicle kilometres with electric propulsion by scenario

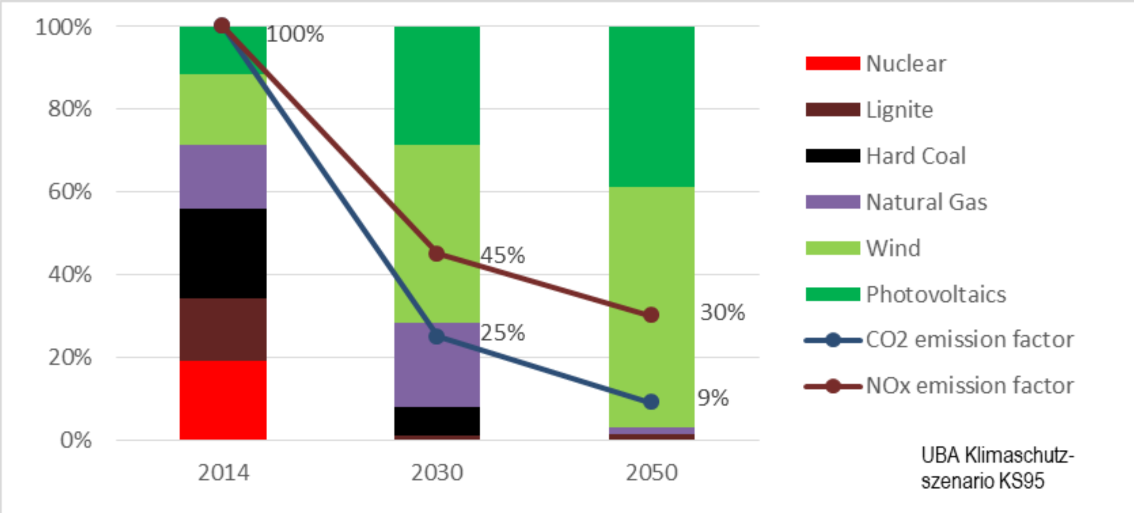
		Road		**Rail**	
Scenario	Year	RALP	NSB	RALP	NSB
BAU	2015	0%	0%	90%	81%
	2030	5%	3%	94%	89%
	2050	10%	8%	100%	100%
Pro Rail	2030	5%	3%	90%	89%
	2050	10%	8%	100%	100%
Pro Road	2030	60%	50%	90%	89%
	2050	100%	80%	100%	100%
Mod Rail	2030	5%	3%	90%	89%
	2050	10%	8%	100%	100%
Mod Road	2030	30%	25%	90%	89%
	2050	50%	40%	100%	100%

3.1.6 Growth of renewable energies

One of the most important preconditions for the success of electric vehicles is the decarbonisation of energy production. This study relies on the Climate Protection Scenario 95% (KS95) developed by the German Ministry for the Environment (Repenning et al., 2015) that has the target to reduce greenhouse gas emissions by 95% in 2050 relative to 2005. As depicted in Figure 1 renewable energies will make up 97% of the German energy production by then. The KS95 scenario was selected in order to show which additional impacts a shift from road to rail and the implementation of new technologies (see above) would generate in a climate friendly environment.

The carbon content of the primary fuels used for electricity production the CO_2 intensity of electricity production declines drastically to 25% in 2030 and to 9% in 2050 compared to 2015 levels. For nitrogen oxides (NO_X) the decline is less steep, reducing 2015 emission factors to 45% in 2030 and finally to 30% in 2050 (compare Fraunhofer ISI and DVGW 2018).

Figure 1: Energy by fuels, Germany, KS95 scenario



Source: Fraunhofer ISI

3.1.7 Proliferation of information technologies in transport

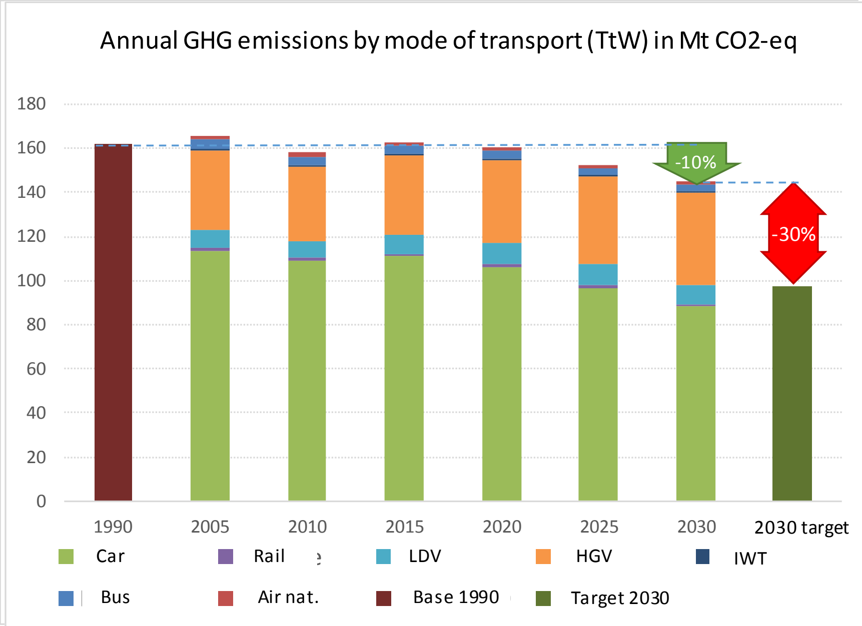
The fast development of new technology applications in the transport sector, such as autonomous driving, driver assistance programmes, safety devices, navigation and improved tools for freight transport management will continue in the future and have strong impacts on costs, emissions and safety. These cost implications were discussed in detail in the respective Working Papers 5 and 6 of the LowCarb-RFC study.

Additionally, autonomous driving and platooning technologies allow more efficient driving performance in road haulage and, to a lesser extent, in rail transport. Through full automation we assume a 10% efficiency gain in trucking in the Pro Road scenario, and of 5% for rail services in the Pro Rail scenario.

3.2 Climate impact assessment

Climate impacts in Transport constitute the leading sustainability indicator for the LowCarb-RFC study. Among all the challenges which transportation is facing, including safety, air quality and noise, climate change has the most profound and long term impact on ecosystems and human living conditions on a global scale. While other sectors managed to curb greenhouse gas emissions, transportation widely fails achieving its mitigation targets. Current model estimates for the German Mobility and Fuels Strategy indicate, that despite the agreed target of -40% GHG emissions by 2030 an actual reduction of only -10% is likely.

Figure 2: Projections and target of German GHG emissions



Source: Fraunhofer ISI / M-Five GmbH

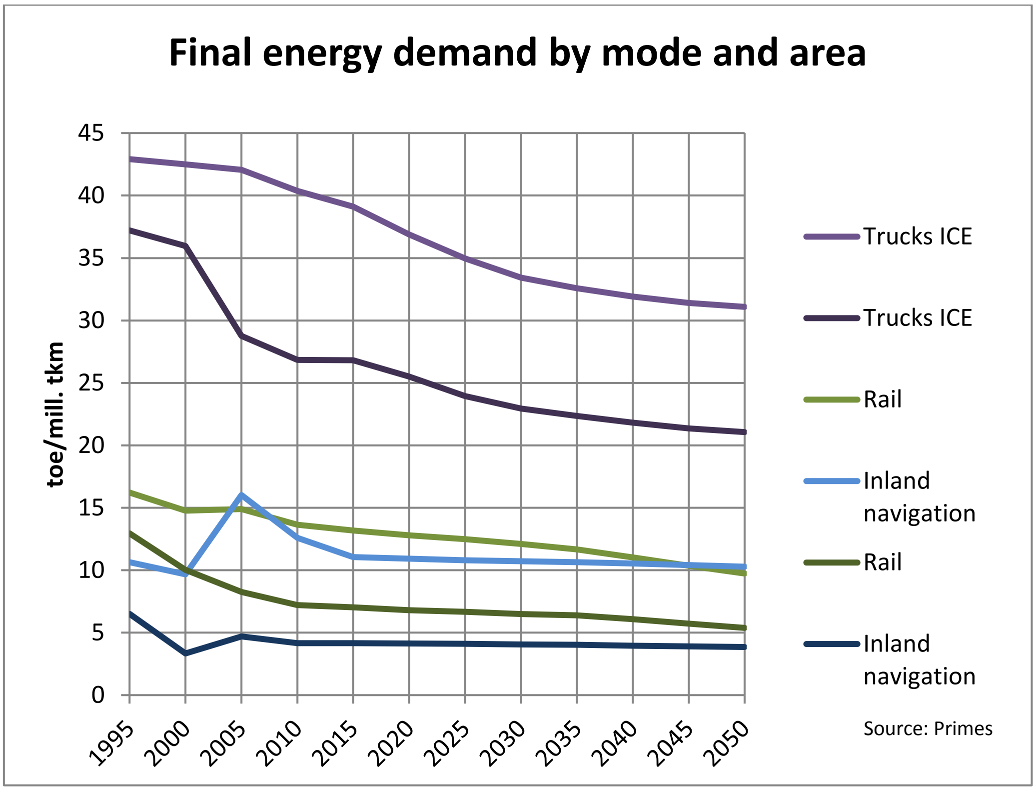
Due to its importance, in this assessment paper we provide climate change impacts via physical indicators as well as by external costs.

3.2.1 Physical greenhouse gas emissions

Physical climate effects are expressed in tons of CO_2 equivalents emitted in the respective years. The calculations include upstream processes for the supply of fossil fuels (well-to-tank) and electricity. The overall emissions are determined through the transport volumes in ton kilometres by mode, corridor and scenario and by the related emission factors.

Emission factors from ICE propelled vehicles are derived from van Essen et al. (2011) for the year 2008 and are indexed to the base year of the LowCarb-RFC study 2015 with the HBEFA 3.3 database (HBEFA, 2017). The comparison shows that, in contrast to air emissions, GHG emissions of HGVs over the past decade have not changed dramatically. Future developments are based on the findings developed in the PRIMES model (E3MLab / AUTH, 2014) and depicted Figure 3. A strong increase in energy efficiency is observed in road transport, while railways are already efficient in 2015. Forecasts of emission factors to 2030 and 2050 are done in accordance to the BAU, Pro Road and Pro Rail Scenarios in Working Papers 5 and 6 of the LowCarb-RFC study.

Figure 3: Development of energy efficiency in freight transport 1995 to 2050 as estimated by the PRIMES model

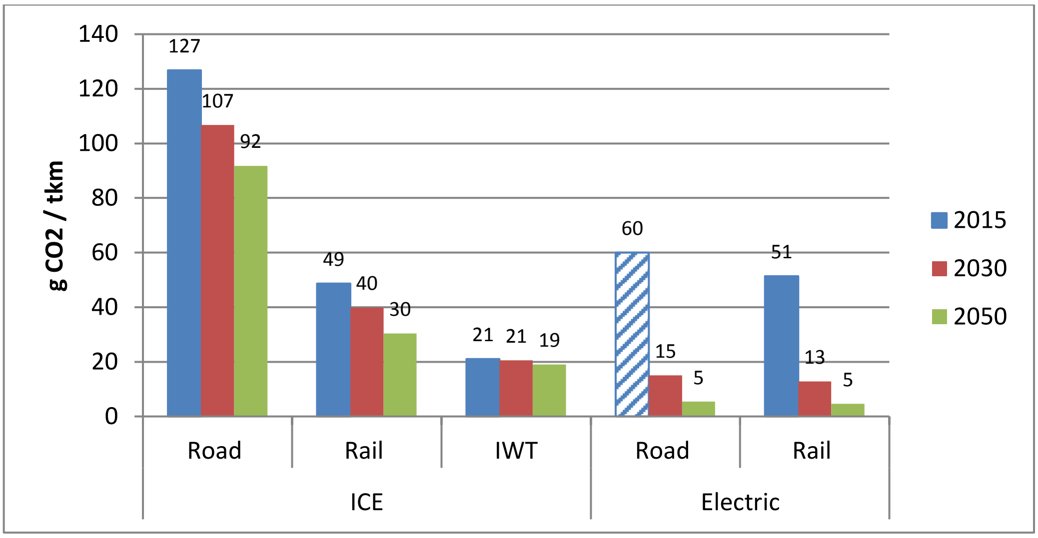


Source: Fraunhofer ISI with PRIMES data

The emission factors for rail are based on the GHG accounting published in DB's integrated annual report 2016 (Deutsche Bahn, 2018) and earlier editions. This includes traction energy as well as all other energy demand attributed to rail freight, such as buildings, services, etc. Energy consumption is assumed at 97.2Kwh/1.000tkm.

For road electric propulsion the emission factors are derived from Wietschel et al. (2017) and the following parameters for hybrid overhead wire trucks are assumed: 1.5kWh energy consumption per vehicle kilometre, 50% load rate including empty headings and unused capacity in loaded trucks resulting in 13.2t average payload per vkm and an emission factor of 192g CO_2/kWh. Values for 2015 and 2050 are extrapolated from the 2030 values using the KS95 development shown in Figure 1. The 2015 column for electric road is shaded as presently there are no electrified trucks in operation. The emission factors for other modes are taken from van Essen et al. (2011) with Primes assumptions for future years and Helms et al. (2016) for upstream effects.

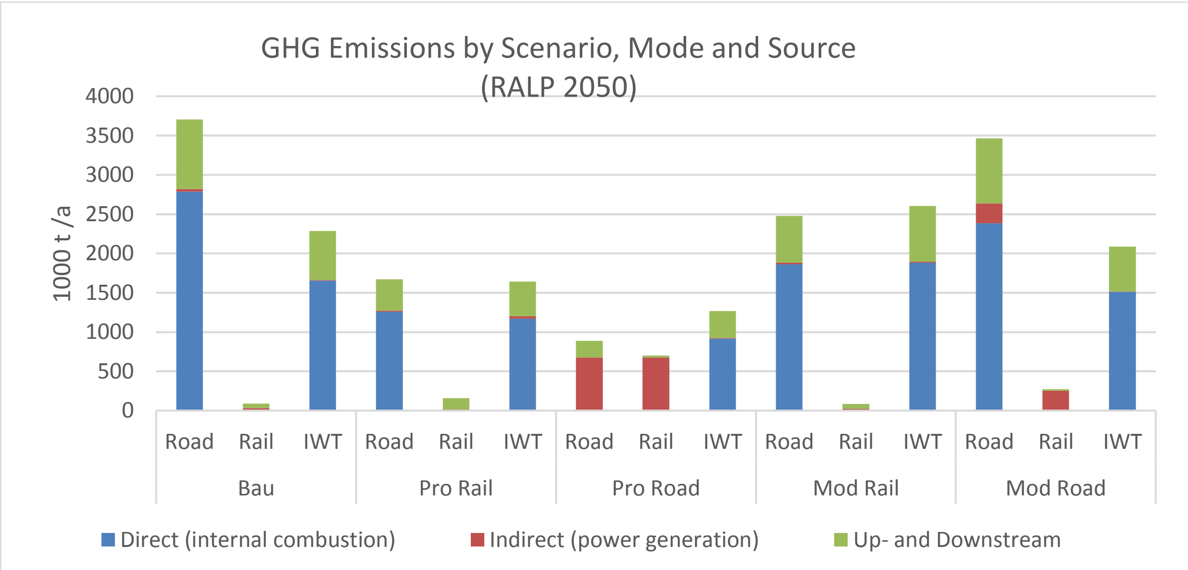
Figure 4: Development of WtW CO_2 emission factors



Source: Fraunhofer ISI

Given the above deliberations, specific CO_2 emissions will decrease as depicted in Figure 4. The switch to renewable power generation with a high share of solar and wind, entails much deeper cuts in GHG emissions compared to the improvement of conventional combustion engines. Therefore, in 2050 the largest share of CO_2-emissions on the Rhine-Alpine-Corridor is produced by ICE as presented in Figure 5.

Figure 5: Sources of GHG emissions 2050 on the RALP corridor



Source: Fraunhofer ISI

3.2.2 External costs of climate change

The external costs of climate change are derived for each scenario from physical emissions by multiplying the greenhouse gas emissions with the specific social costs per ton of CO_2-equivalents. Estimating CO_2 costs is tricky due to their global and long-term impact on various aspects of human life and the ecosystem. Monetary costs per ton of CO_2-equivalent emitted can be approached via estimating potential damages or by estimating avoidance efforts needed to remain below certain atmospheric CO_2 concentration. In both cases studies arrive at wide ranges and a progressive slope of potential unit values towards future years. The latter is due to the approach of tipping points in the global ecosystem and the more and more limited availability of cheap mitigation measures.

Table 3 presents three alternative estimates for 2015, 2030 and 2050 elaborated by the German Environment Agency's Methodology Convention 2.0 for the Estimation of Environmental Costs (UBA, 2012a). For this study, we select the central estimate. However, on-going research for the Methodology Convention 3.0 suggests much higher values, which come closer to the upper estimate in Table 3. Sensitivity estimates in the prevailing impact assessment will demonstrate the outcome of both estimates.

Table 3: Specific climate change costs

Unit cost estimates (€/t CO_2-eq)	Short-term 2015	Mid-term 2030	Long-term 2050
Low estimate	40	70	130
Central estimate	80	145	260
High estimate	120	215	390

Source: Fraunhofer ISI and DVGW (2018), updated from UBA (2012a)

Additionally, upstream effects are caused by greenhouse gases emitted during the production of the vehicles and the provision of fuels and electricity.

3.3 Air pollution impacts

From the cocktail of engine and non-engine caused air emissions the sustainability assessment in this paper concentrates on the leading substances with greatest relevance for human and natural health: nitrogen oxides (NOx) and particulate matter (PM).

For diesel trucks motor related emission data is taken from the Handbook of Emission Factors (HBEFA), version 3.3 (HBEFA, 2017). Table 4 summarises some emission factors from literature. The table shows that even in the past decade NO_X and PM emissions have gone down considerably, and that motorway-specific emissions per ton kilometre are considerably lower than all-network average emission factors. In the contrary, the emissions from abrasion and resuspension are remarkably constant across the sources, years and traffic situations.

Table 4: Literature review of emission factors for HGVs

Source	Year	HGV type	Road type	CO_2 (motor)	NOx (motor)	PM total	$PM_{2,5}$ (motor)	PM_{10} (abra sion) [2]	PMcoarse (resus-pen-sion)
UBA, 2018	2016	>3,5t	All	104,0	0,26		0,003		
HBEFA, 2017 [1]	2015	>3,5t	MW	58,4	0,11	0,007	0,002	0,005	
	Euro-VI	>3,5t	MW	59,2	0,02	0,003	0,000	0,003	
Doll et al., 2016	2015	>12t	All	137,2	0,46	0,009			
	2030	>12t	All	134,2	0,19	0,000			
van Essen et al., 2011	2008	>3,5t	All		0,84	0,046	0,014	0,018	0,014
BASt, 2009	2008	40t	MW			0,012	0,008	0,005	

Legend:
[1] g/vkm transformed into g/tkm with a load rate of heavy trucks on motorways of 15.0t/veh.
[2] Includes some $PM_{2.5}$ particles. Source: compiled by Fraunhofer ISI

For 2030 it is assumed that these regulated motor-created NO_X and $PM_{2,5}$ emissions decline to the level of today's Euro-VI diesel engines. For 2050 a further decline by 50% is assumed.

For other modes the following sources are used: van Essen et al. (2011) for road and rail diesel emissions in 2015 and Doll et al. (2016) for future projections to 2030 and 2050. For rail diesel traction, it is assumed that the EU Directive 97/68/EC on non-road mobile machinery (NRMM) is implemented for rail engines by EC directive 97/68/EC (EC 1997) and thus the same improvements as for ICE road vehicles will take place.

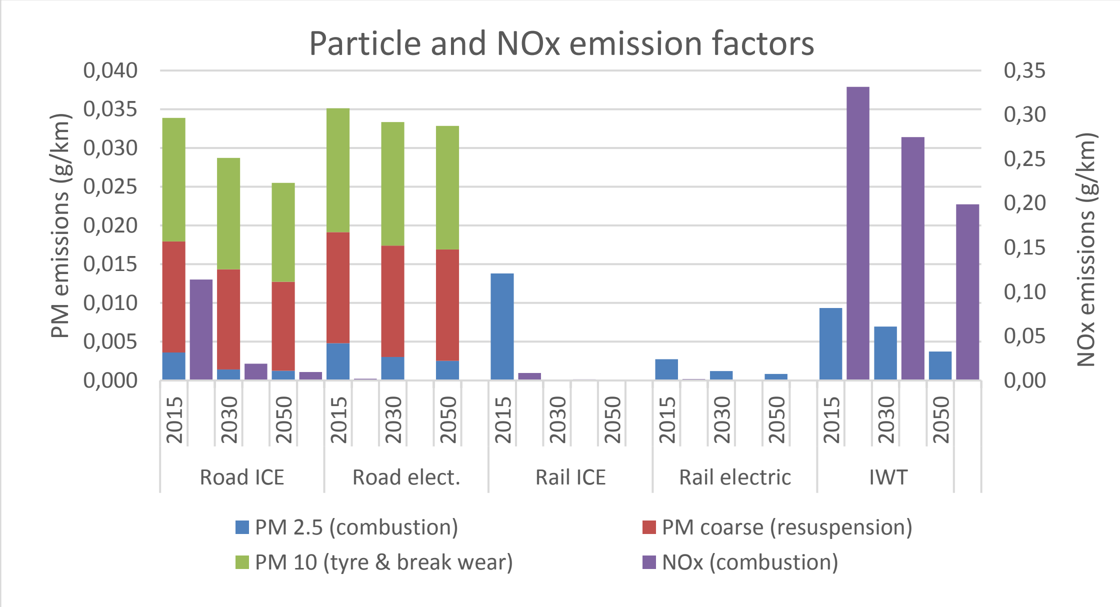
Emissions from inland water vessels are assessed based on emission factors presented by UBA (2012a) and projecting future emissions as according to the BAU scenario for barges presented in PANTEIA (2013).

For electric vehicles van Essen et al. (2011) deliver the basis for 2015 and the future projection is done by applying the changes assumed in BMUB's Klimaschutzszenario which considers pollutant emissions from future power plants. The electricity mix and specific emissions per type of power plant for 2015, 2030 and 2050 are taken out of Fraunhofer ISI and DVGW (2018) for Germany. It is assumed that these values more or less are valid for all corridor countries.

Nitrogen oxides (NOx) and particle matter <2.5 µm (PM 2.5) serve as reference pollutants as these play the core role in current legislation on national and local emission ceilings. We however acknowledge that particularly in the shipping sector sulphur dioxide (SO_2) and other compounds are still not completely eliminated from exhaust streams.

Emissions of particulate matter PM are determined by exhaust and tyre and brake abrasion. Generally it can be said that the small $PM_{2.5}$ particles mainly stem from fuel combustion, the larger PM_{10} particles are subject to break and tyre wear and the largest PM_{Coarse} diameters can most be found in dust resuspension from the road surface. For reasons of simplicity non-exhaust emissions from abrasion and resuspension are considered constant, although low wear tyre rubbers and break technologies together with well-maintained road surfaces could significantly lower PM_{10} and PM_{Coarse} emission factors. Another simplification is made for rail transport, for which no abrasion emissions are estimated. On the other hand we have included PM emissions from electricity production without a major decline towards 2050, while we did not include the air pollutants from fuel production. These assumptions appear acceptable as in terms of health impacts the small $PM_{2.5}$ particles are way more harmful and thus more relevant for the external costs.

Figure 6: Emission factors for $PM_{2.5}$, PM_{10}, PM_{Coarse} and NOx by mode and propulsion 2015, 2030 and 2050



Source: Fraunhofer ISI

- The specific cost per tonne of pollutant is based on the Federal Environment Agency's Methodology Convention 2.0 (UBA, 2012a). Unlike greenhouse gas unit costs, the unit costs for NO_X and particulate matter do not progress over time. For PM the Methodology convention provides unit costs for the categories "coarse" and PM_{10} in addition to $PM_{2.5}$. The first two categories are relevant for resuspension in transport and for power plant emissions.

Table 5: Specific costs for air pollutants [Euro/ton of pollutant]

Pollutant	NO_x	$PM_{2.5}$	PM_{10}	PM_{coarse}
Unit costs 2015 to 2050	15,400	55,400	39,700	2,900

Source: UBA Methodenkonvention 2.0, p. 9

3.4 Noise impacts

The number of citizens disturbed by transport noise is reported by the Federal Environment Agency (UBA) in line with the EC's "Environmental Noise Directive". The latest available account is from 2012 (UBA, 2012b). The specific noise costs were derived from cost figures provided by UBA (2012a) that had to be adjusted to night and day as well as heavy and light vehicles. Since long distance freight transport is running at speeds around 80km/h where rolling of tyres outvoices engine noise, electric vehicles emit similar noise levels as ICE vehicles. Only transports outside urban areas are included. Barge transport is assumed to not exceed day or night noise target levels and thus do not cause external costs.

Table 6: Specific costs for noise emissions [Euro/veh.km]

Transport mode	Road freight	Rail freight	Barge transport
Unit noise costs 2015 to 2050	1.16	54.10	0

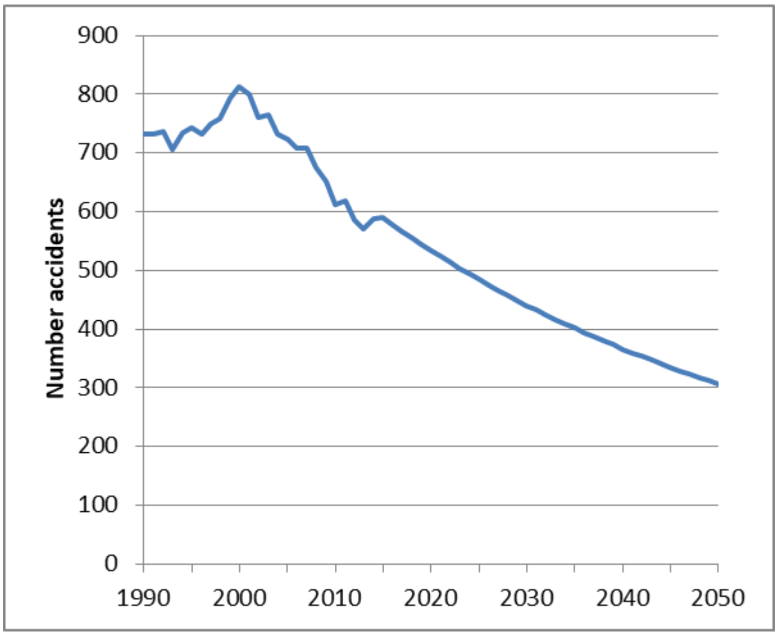
Source: UBA Methodenkonvention 2.0 p.18f, own calculations

3.5 Transport safety impacts

In the past 27 years European road transport experienced a tremendous improvement in safety, which was mainly caused by a number of new technologies, such as driver assistance programmes and anti-blocking brakes. Since the development of these technologies is continuing with an even greater speed, it can be safely assumed that traffic accident rates will continue to decrease in the future.

Based on historic truck accident rates on German motorways between 1990 and 2015 we project a further halving truck-inflicted crashes as shown in Figure 7. Since the fatalities and injuries decreased as well, it can be estimated that up to 2050 the number of fatalities will decrease by 83%, of severe injuries by 71%, while the number of slight injuries will be halved.

Figure 7: Past and projected HGV accident rates on German motorways 1990 to 2050



Source: Eurostat, own calculations

The number of casualties is derived by multiplying the transport volumes on the corridors with the adjusted accident rates of freight vehicles on German motorways. We assume that accident rates on motorways on the other corridor countries do not differ considerably from the German rates, and thus the latter are used along the entire corridors. The external costs are derived using the figures given in Table 7.

Table 7: External costs per casualty (euros)

Type of casualty	Fatality	Severe Injury	Slight Injury
Social costs 2015, 2030 and 2050 [Euro]	2,220,000	307,100	24,800

Source: UBA Methodenkonvention 2.0, p. 23

Accidents caused by rail freight are only relevant at railway crossings, where 90% are caused by road users. Since in Germany statistically less than one person would be killed by freight trains annually, rail accidents are disregarded.

3.6 Travel time, reliability and other externalities

Travel time and reliability can be assessed economically in a similar way to the environmental and safety impacts above. However, time and reliability are two of the major determinants of the quality and of transport services and are thus consciously taken into account by shippers when choosing a transport option.

Therefore, and because time and reliability advantages do not impose costs or benefits to third parties in the way climate, air and noise emissions or accident consequences to, such quality-related impacts are not an externality of the transport sector. They are only external to single transport users as competing for scarce infrastructure means causing impacts in the form of delays to other transport users.

Considering the above we refrain from assessing the economic costs or benefits of travel time, delays, reliability or any other transport-specific quality indicator. Details on transport quality indicators can be found in Working Paper 5 for the rail sector and in Working Paper 6 for road haulage.

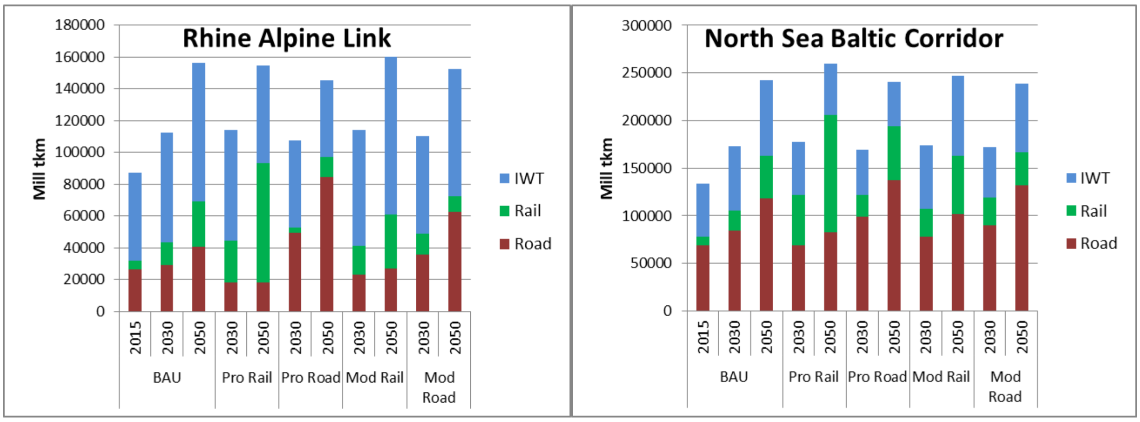
Other external effects, such as vehicle production, infrastructure supply, nature and landscape, soil and water, as well as loss of biodiversity are not included in the calculations.

4 Sustainability assessment results

4.1 Transport volumes

The output of the scenario model calculations are presented in Figure 8 and Figure 9. All scenarios show a considerable increase (59%-103%) in transport volume up to 2050. This reflects the increase in goods transport that has been observed already in the past decades. The changes in transport volumes can be explained by the rebound effects generated by lower transport costs, which reach nearly 60% in the Pro Rail scenario. Opposite, the Pro Road scenarios assume a cost increase for rail transport of one third, which results in an enormous increase in road transport. These changes have considerable impacts on the external costs as well.

Figure 8: Transport volumes on the corridors 2015 to 2050



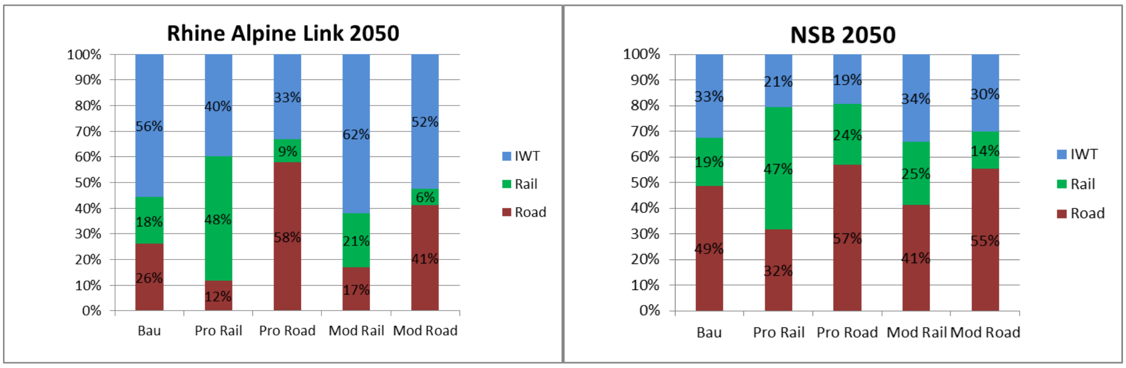
Source: van Hassel et al. (2018)

Obviously, the share of rail freight in 2050, depicted in Figure 9, is highest in both rail scenarios, reaching up to 48% on the RALP corridor in 2050 and reducing road freight to only 12% compared to 26% in BAU. The same fact holds generally true for the North-Sea-Baltic Corridor as well, with the road share being reduced to 32% compared to 49% in BAU.

On the other hand, the Pro Road Scenario increases its modal share to nearly 57% and 58% in both corridors, leaving rail with only 9% on the Rhine Alpine Corridor and 24% on the North-Sea-Baltic corridor in 2050.

Interestingly, the moderate Scenarios 2050 (Mod Road Mod Rail) are not representing an intermediate situation between BAU and Pro-Scenarios. Especially on the Rhine corridor inland barges are taking a larger share of the transport volume compared to BAU, reaching up to 62% in Mod Rail 2050. Apparently, the price changes assumed in the scenarios (see chapter 2) provide strong incentives for inland water transport and reduce the rail share along the Rhine to only 6% in Mod Road 2050.

Figure 9: Modal share on the corridors 2050



Source: van Hassel et al. (2018)

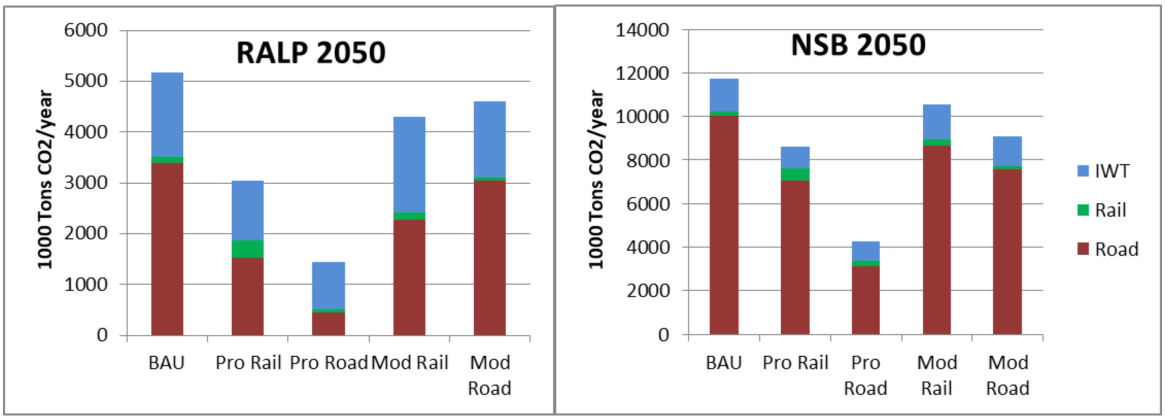
4.2 Physical impacts

This chapter describes the physical effects of the above transport model calculations on emissions and road safety.

4.2.1 Climate impacts

The combination of the above described measures, especially the change to electric propulsion and the decarbonisation of energy production, will have a strong impact on greenhouse gas emissions. The Pro Road Scenario cuts the CO_2 emissions of the BAU scenario by 72% in the RALP corridor and by 64% in NSB corridor, while the Pro Rail only reaches a reduction of 41% on the RALP and 26% on NSB corridor. Both Mod-Scenarios produce moderate impacts compared to BAU.

Figure 10: CO_2 emissions in 2050

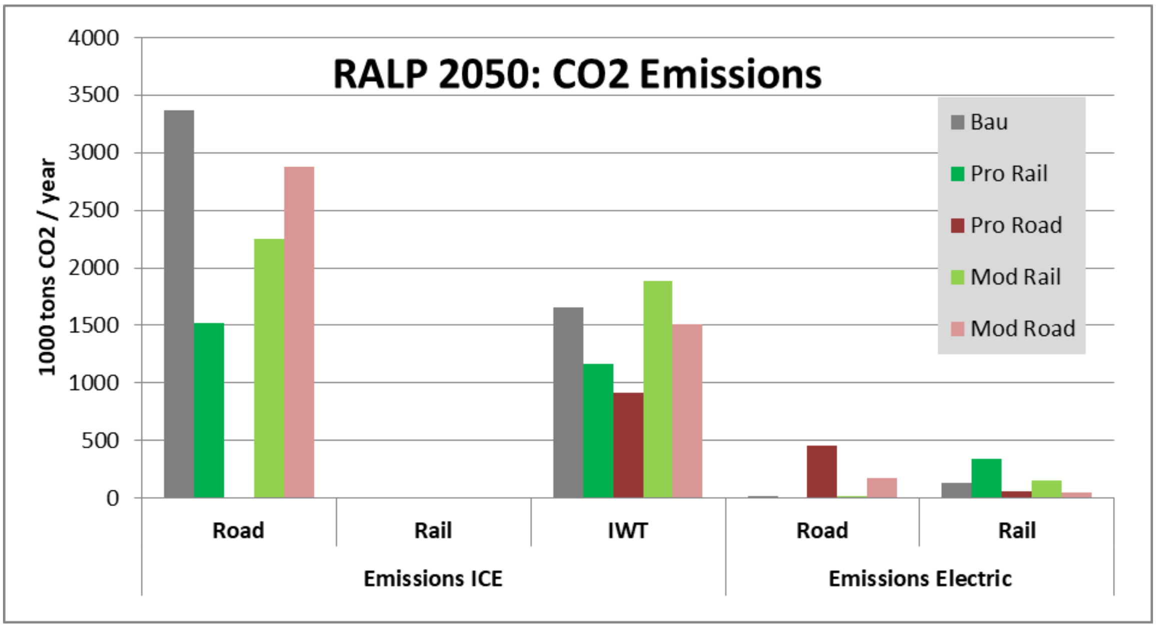


Source: Fraunhofer ISI

The explanation for this phenomenon is provided in Figure 11 which breaks down the sources of CO_2 emissions by modes. In 2050, ICE engines produce the largest share and the large volumes transported on the water are a major additional source of greenhouse gas emissions. However, there are no more Diesel trains running and all motorways will be electrified in the Pro Road Scenario. The latter has a profound impact on the outcome of the scenario because no matter how much traffic trains and water barges manage to attract, the bulk of goods will remain on the road. Practically eliminating greenhouse gas emissions there constitutes a huge step towards a climate-neutral freight transport sector. Due to its systemic limitation, rail is bounded in its ability to contribute there. Assuming that only half of HGV traffic runs electric in the Mod Road scenario, in contrast, CO_2 emissions will more than double compared to the Pro Road case.

The road based climate mitigation strategy is indispensable, but it comes with some risks. First, all trucks using the corridors need to go electric. In the liberalised and international European haulage market, the enforcement of a zero-GHG standard might prove difficult even under a 2050 time horizon. Second, the energy transition must progress as predicted in the KS95 scenario. If progress is considerably weaker, the strong advantage of the Pro Road over the Pro Rail scenario will melt away.

Figure 11: Sources of CO_2 emissions in 2050



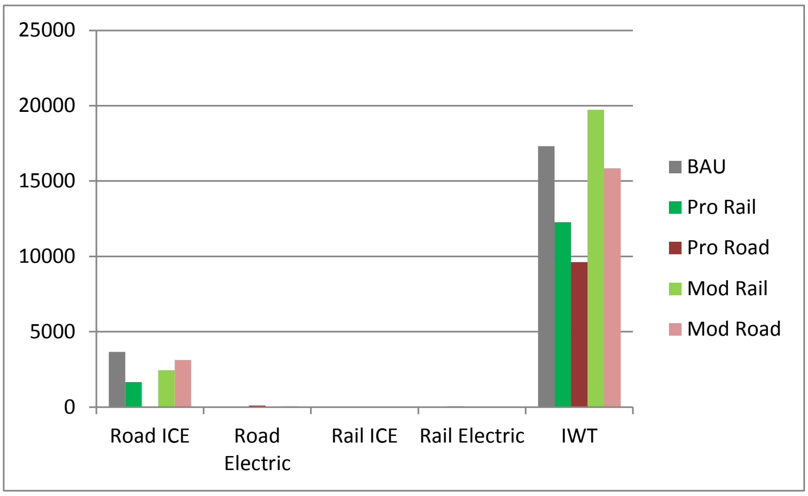
Source: Fraunhofer ISI

Electrifying all of road transport by 2050 is not totally impossible, but extremely ambitious. A scenario close to the Mod Road case seems thus more likely to emerge than a situation close to the Pro Road case. From the narrow perspective of CO_2 emissions we can thus conclude that road haulage decarbonisation needs to be addressed decisively, but we need more goods on rail as a default solution and to stabilise future climate mitigation pathways.

4.2.2 Air pollution impacts

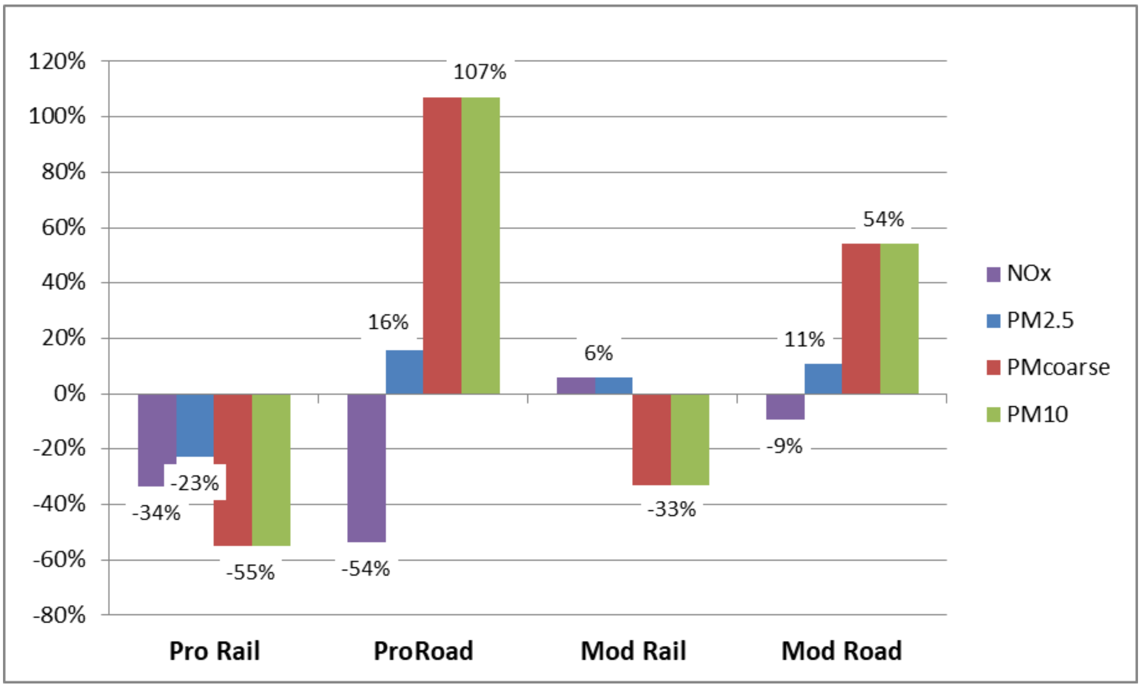
The impacts on air pollution can be best explained by presenting the NOx emissions on the RALP corridor in 2050 as depicted in Figure 12. Obviously, inland water barges are the major source of pollution in 2050. One cause is the large share on the transport volume. Additionally, it was assumed that compared to ICE trucks only moderate improvements of emission technologies are applied (BAU scenario, PANTEIA 2013). All vehicles with electric propulsion are practically emitting no NOx due to the renewable energy supply. In 2050, no Diesel trains will be operating and no ICE trucks in the Pro Road Scenario.

Figure 12: NOx emissions on the RALP corridors in 2050



Source: Fraunhofer ISI

Figure 13: Pollutant emissions in 2050, BU and RALP Corridor



Source: Fraunhofer ISI

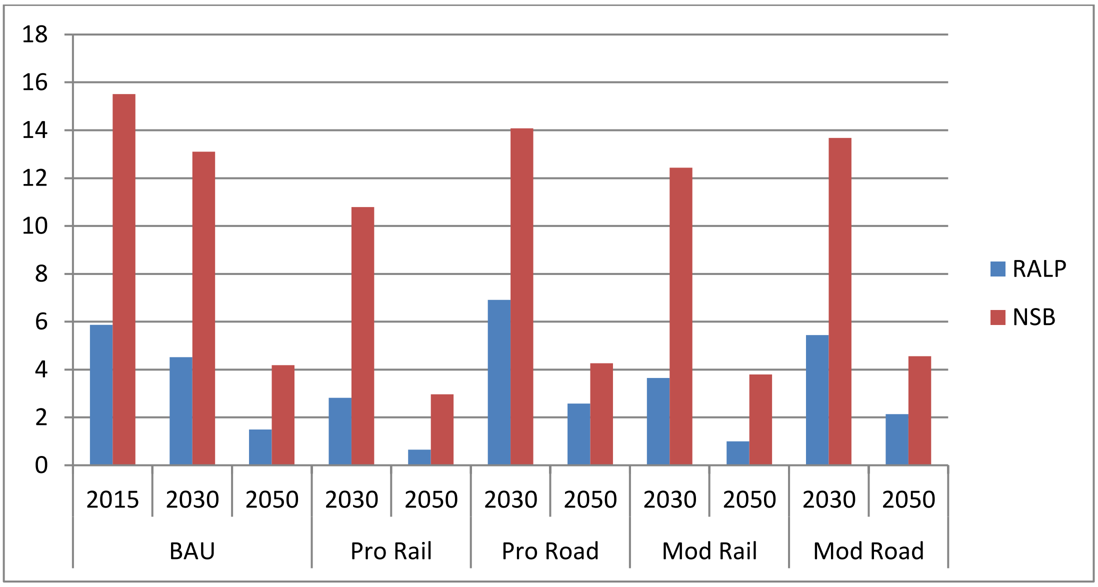
Other pollutants: Figure 13 compares the pollutant emissions in the RALP scenarios with the BAU 2050 case. The Pro Rail scenario reduces all emissions by 23% to 55%. The Pro Road has diverging effects: On one hand NOx emissions are cut into half due to exclusive electric propulsion. On the other hand, the particulate emissions ($PM_{2.5}$ and PM_{coarse}) derived from tyre abrasion more than double, due to the larger transport volumes on roads. The moderate scenarios show similar effects as the Pro-Scenarios. The different values of particulate emissions can be explained by the variation of road transport volumes in the scenarios.

Similar effects as described above using the example of the Rhine corridor are apparent as well on the North-Sea-Baltic corridor.

4.2.3 Transport Safety

The development of transport safety is strongly correlated with the transport volume that is increasing in all scenarios. However, the strong increase was compensated for by the even faster improvement of transport safety, explained in Chapter 3.1.7. Since corridor transports are mainly taking place on motorways, which are the safest type of roads, the number of fatalities given in Figure 14 is fairly low in all corridors. This holds true as well for injuries. Obviously, the Pro Rail scenario causes the least casualties, improving safety enormously even compared to 2015, where traffic volumes are higher. In contrast, the Pro Road Scenario causes a larger number of victims compared to 2015 and to the other scenarios.

Figure 14: Number of fatalities in the scenarios



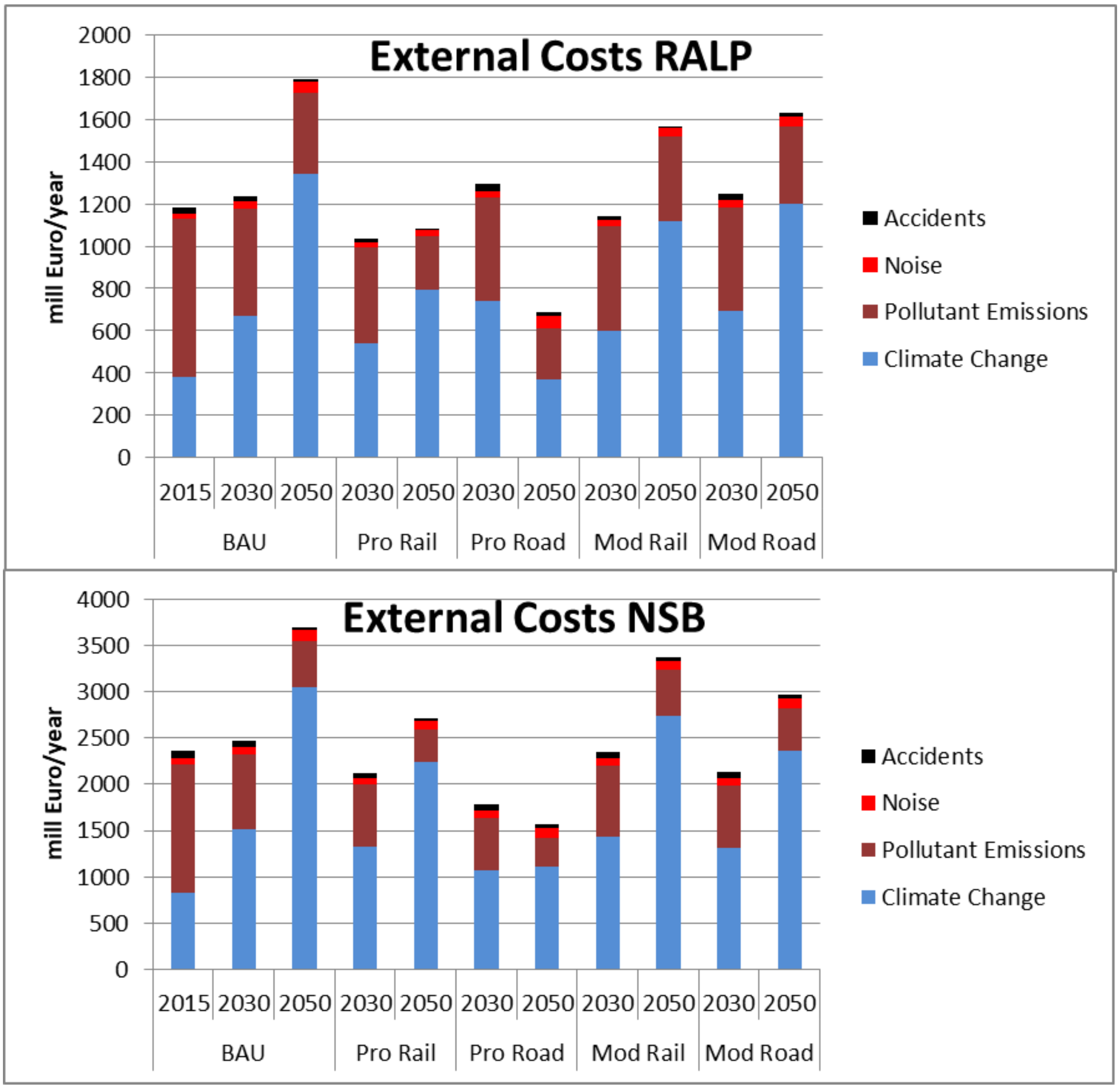
Source: Fraunhofer ISI

4.3 External costs

4.3.1 Total external costs

External costs are primarily determined by the expected strong increase in transport volume as described in chapter 4.1. Total costs increase in the BAU scenario by more than half, while the Pro Road Scenario manages to reduce external cost by 34% to 42% in the corridors compared to 2015. This is remarkable, since not only road volumes increase during this time period, but as well the costs for CO_2 emissions as described in chapter 3.2.

Figure 15: External Costs according to effects



Source: Fraunhofer ISI

A slight cost reduction (-8%) can be observed only for the Pro Rail Scenario in the RALP corridor, while all other scenarios result in cost increases in both corridors compared to 2015.

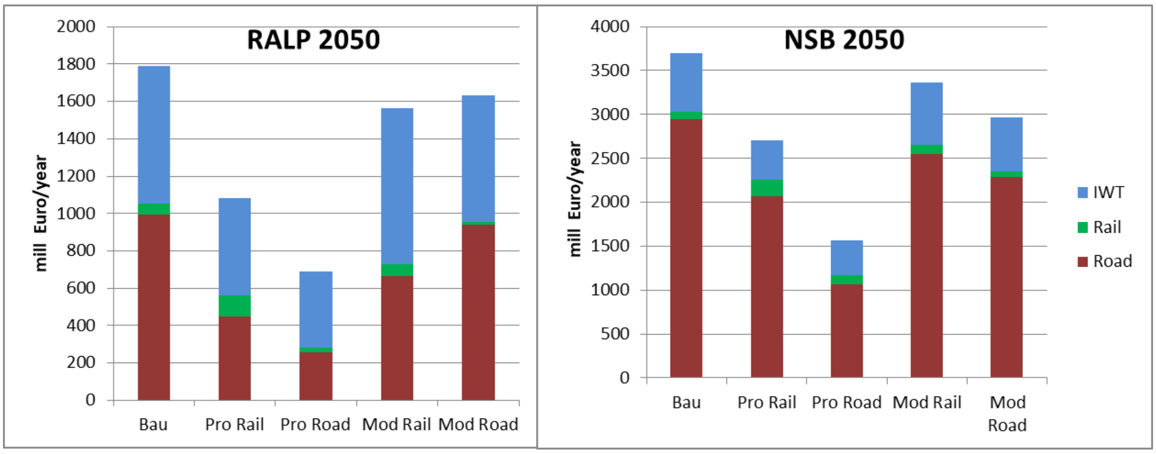
Climate change costs represent the largest share, followed by air pollution. Noise and accidents do not play an important role here, since noise affects only few residents near motorways, accident rates on the motorways are fairly low and additional technical improvements, in particular automated and autonomous driving, will reduce the number of casualties on motorways by 2050 even further.

4.3.2 Comparing the costs in the 2050 scenarios, External costs by mode of transport

Figure 16 reveals that all scenarios reduce external costs compared to BAU. However, cost reductions are best in the Pro Road scenario with a decrease around 60%, followed by Pro Rail with 40% in the RALP corridor and 27% on the NSB track. The weaker performance in the NSB corridor can be explained by the larger share of non-electric trucks. Both moderate scenarios produce only modest improvements between 9% and 20%.

External cost reductions in the Pro Road Scenario amount to 1.1bn Euro p.a. on the RALP corridor and to 2.1bn Euro p.a. in the NSB corridor.

Figure 16: External cost according to modes 2050

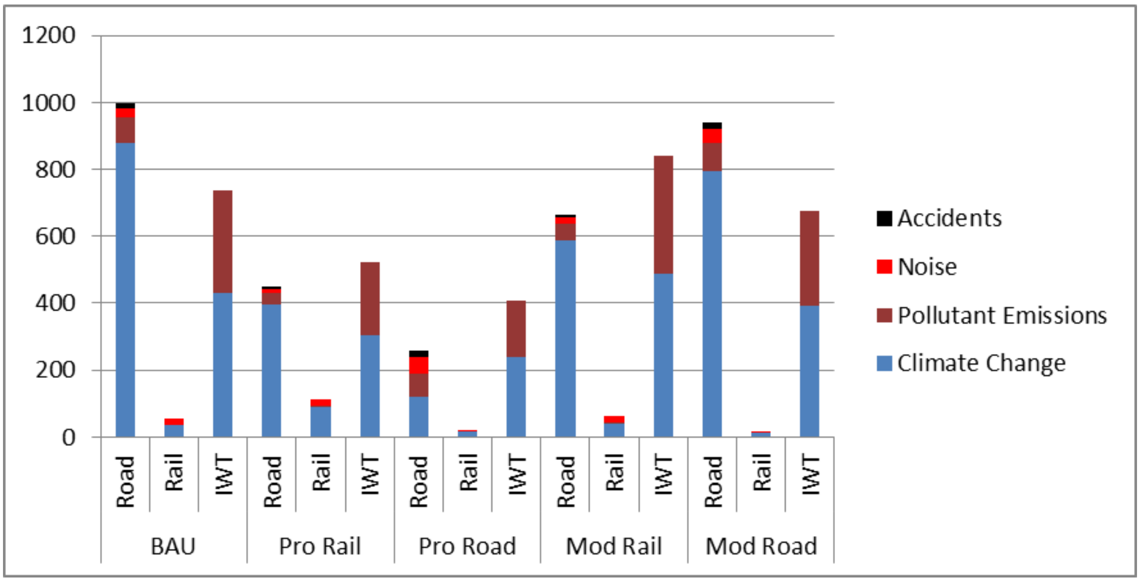


Source: Fraunhofer ISI

4.3.3 External costs by mode of transport

Remarkable is as well the small share of external rail costs which is depicted best in Figure 17 using the example of the Rhine Alpine Corridor. Even though external rail costs are close to negligible, the Pro Rail scenario is not performing better than Pro Road. Again, the explanation is that in both road scenarios an electrification of the motorways is foreseen, while the rail scenarios are not accompanied by electrification of motorways. As a consequence, of the emission factors and unit cost assumptions, the remaining share of trucks and inland barges generates the lion's share of external costs in the Pro Rail and Mod Rail scenarios. Main drivers are CO_2 and pollutant emissions.

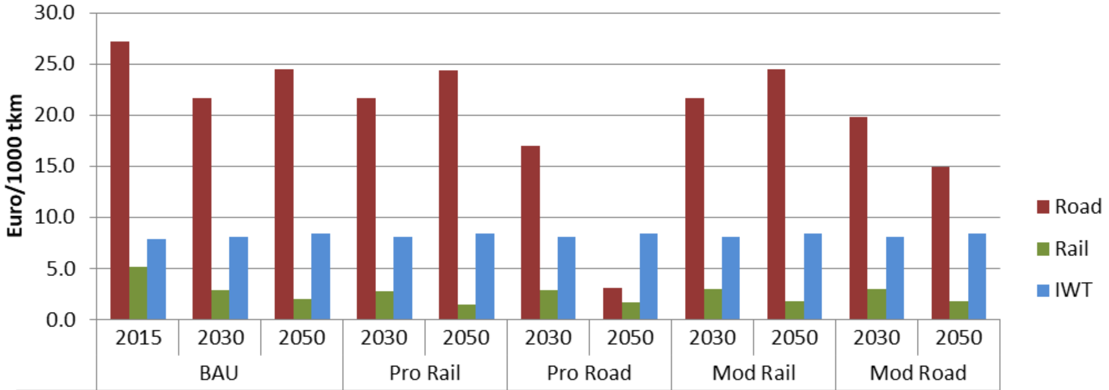
Figure 17: External Costs on the RALP corridor 2050



Source: Fraunhofer ISI

The average external costs per 1,000 kilometres are depicted in Figure 18 using the RALP corridor as an example. Clearly, road costs are highest, but varying with the scenarios. Costs for inland water shipping remain constant over all scenarios. Cost on the NSB corridor do not differ significantly.

Figure 18: Average external costs on the RALP corridor



	2015	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050
	BAU			Pro Rail		Pro Road		Mod Rail		Mod Road	
Road	27.2	21.6	24.5	21.6	24.4	17.0	3.1	21.7	24.5	19.8	15.0
Rail	5.2	2.9	2.0	2.8	1.5	2.9	1.7	3.0	1.8	3.0	1.8
IWT	7.9	8.1	8.5	8.1	8.5	8.1	8.5	8.1	8.5	8.1	8.5

Source: Fraunhofer ISI

4.4 External cost efficiency

4.4.1 Investment costs

The Pro Rail scenario described in Doll and Köhler (2018) cites capacity expansion costs for the rail network of 440 million euros annually over 50 years for a doubling of network capacity (Holzhey et al., 2010). Computing annual payments with an investment horizon of 40 years and an interest rate of 3% leads to additional costs per extra freight volumes catered by the rail network of 0.08 €-Ct./tkm.

We cross-check this figure by two alternative calculations: bottom-up with usual investment and capacity figures of the networks and top-down with cost and volume growth scenarios of the German federal investment plan.

The bottom-up calculation uses a 3% interest rate and the following parameters for road and rail. For IWT we assume enough free capacity and thus zero expansion costs.

- Road: 15 mill. Euros per motorway-km. With 50% running costs we get 0.97€ annual costs. Traffic volumes are 20,000 trucks per day over 250 days per year and a load factor of 15 tons per truck.
- Rail: 35,000 € per track-km with a 60 year lifetime and 25% running costs above capital costs. This is 1.58 million € annual costs. Traffic volumes are 100 freight trains per over 360 days with 500t payload per train.

The top-down approach applies the standard scenario of the German federal investment plan (BVWP) 2030. The investment figures are given jointly for road and rail transport, so first a ton kilometre equivalency (tkm-eq.) factor per passenger kilometre is estimated to get the hypothetical freight volumes which could be accommodated by these investments. This intermediate step is not required for IWT as here only freight is considered.

- Road: We assume 5% buses with 30 passengers using two passenger car units of road space, and 95% cars with 1.4 passengers, which leads to a load rate of 2.1 people per car. Trucks on motorways load 15 t and require 2 passenger car units, which leads to a tkm-eq. of per pkm in road transport of 3.6. Investment plan forecasts then lead to 509 billion tkm-eq. more in 2030 compared to 2010. This requires 49.7 bn. € investment costs plus 50% maintenance expenditures. Finally we receive 0.01 €/tkm-eq. of capital and running costs.
- Rail: 500t versus 250 passengers per train, both requiring the same network capacity. With a tkm-eq.-factor of 2.0 we get 78.3 billion additional tkm-eq. for rail, which costs 40.1 bn. Euros 2010 to 2030. This leads to additional capital and maintenance (25% of capital) costs of 0.04 €/tkm-eq.

Table 8 summarises the additional network related capital and running costs obtained from the approaches described above. The figures according to UBA (2010) are based on an advanced perspective on the development of the rail network, including full use of digital technologies, longer trains, etc. Eventually, the cost per tkm-eq. received ranges a factor 10 below the bottom-up and a factor 5 below the top-down estimates. Although the latter origin from completely different approaches, they are rather similar in magnitude. Both have in common that they assume today's capacity allocation processes still in place in 2030 and are thus to be considered conservative.

Table 8: Comparison of infrastructure costs per ton kilometre equivalent

Mode	**Holzhey et al. 2010** €/tkm-eq.	**Bottom-up** €/tkm-eq.	**Top-down** €/tkm-eq.
Rail	0,008	0,088	0,043
Road		0,013	0,010
IWT			0,035

Source: Fraunhofer ISI

For the following computation of cost efficiency indicators we depart from the top down values as they represent a contemporary and multi-project dataset provided by the German federal investment plan 2030 (BMVI 2016). To this data we apply the following modification:

- The BMVI (2030) figures assume an investment period of 20 years, while the scenarios in this study run over 35 years from 2015 to 2030. Translating annuities with a 3% interest rate yields 69% of annual costs under a 35 year investment scenario compare to a 20 year scenario.
- With the 2050 time horizon and advanced production forms for rail capacity allocation in mind we reduce the rail costs to 75% of the original €/tkm-eq.
- Considering the massive over-capacities on the main inland waterways, we consider only 50% of theoretical expansion costs applicable.

We then get 0.7 €-Ct/tkm-eq. for road, 2.2 €/Ct./tkm-eq for rail and 1.2 €-Ct./tkm-eq. for inland waterway transport.

4.4.2 Cost efficiency indicators

In the Business-as-Usual scenario, the TPR chain model estimates an increase of rail volumes from 2015 to 2050 by +500% or 25 billion tkm along the RALP corridor and by 400% or by 50 billion tkm on the NSB corridor. If we do a simple linear extrapolation of the average expansion costs from Table 8 we receive annual costs of two to three billion euros for RALP and five to seven billion euros for NSB to implement the Business-as-Usual scenarios. For cost efficiency indicators, however, we need cost and performance indicators covering equal perids and conditions.

Within the target year 2050, however, external costs can be compared between scenarios and to related annual investment figures. Capital costs from capacity investments and running costs in freight infrastructure are computed as annual values as described above. These cost estimates are very crude. Two major impact factors are disregarded:

(1) The likely strong progression of infrastructure investments with each additional ton kilometre to be accommodated;
(2) Missing upfront and maintenance investments for overhead-wire or similar infrastructures for electric trucks on motorways; and
(3) The existence of operational measures to gain more capacity out of existing infrastructures though operational improvements, novel control systems, as well as facility and rolling stock management.

(4) We have taken the perspective of supporting either road or rail. A combined approach might be superior to these extreme cases. We draft such a case in the conclusion part of this paper.

We assume that both developments for the rail sector might just equal out beyond the technical advancements considered above. For the road sector the merits of operational improvements should be more limited as the sector is already now very competitive. The results of the proposed cost estimates are shown in Table 9.

Table 9: Traffic volumes, costs and cost efficiency indicators 2050 for the Pro Road and Pro Rail scenarios, both corridors

Indicator / transport mode	Unit	RALP Pro Rail	RALP Pro Road	NSB Pro Rail	NSB Pro Road
Shifted volume in tkm-eq. 2050 relative to BAU					
Road	Mill. tkm/a	-21,576	41,966	-34,071	18,354
Rail	Mill. tkm/a	44,860	-14,962	75,852	12,035
IWT	Mill. tkm/a	-24,507	-37,229	-24,538	-31,427
Annual investment (de-investment costs					
Road	Mill. €/a	44	285	69	125
Rail	Mill. €/a	999	100	1,689	268
IWT	Mill. €/a	88	134	88	113
TOTAL	Mill. €/a	1,131	519	1,847	506
External Costs saved against BAU					
Total saving	Mill. €/a	500	1,100	1,000	2,100
Benefit-Cost-Ratio		0.44	2.12	0.54	4.15
Costs per ton of CO_2 saved					
CO_2 emissions saved	Mt CO_2/a	2,0	3,5	3,0	5,5
Mitigation costs	€/t	566	148	616	92

Source: Fraunhofer ISI

Comparing the annual costs 2050 by scenario we find that the estimated investment and running costs for extending the rail network are roughly twice as high as the financial effort needed to expand the motorway system in line with the scenario results. This picture might change as we use progressive construction and maintenance costs for roads and at the same time assume the efficiency programmes of the railways to bear fruits.

The benefit cost ratio of external costs over capacity extension appear negative for the railways and positive for road. This is caused by the major cut in GHG emissions from electric trucks, while the railways do not gain much in sustainability in the Pro Rail scenario. Again, here we dismiss the costs of installing electricity supply infrastructures on motorways.

The costs per ton of CO_2 saved are high and again are clearly more positive for the Pro Road scenarios than for the Pro Rail cases. They range between 616 €/t CO_2eq in the Pro Rail case and 92 €/t CO_2-eq in the Pro Road case. Mitigating greenhouse gases via the road sector appears to be five times more efficient than via the railways.

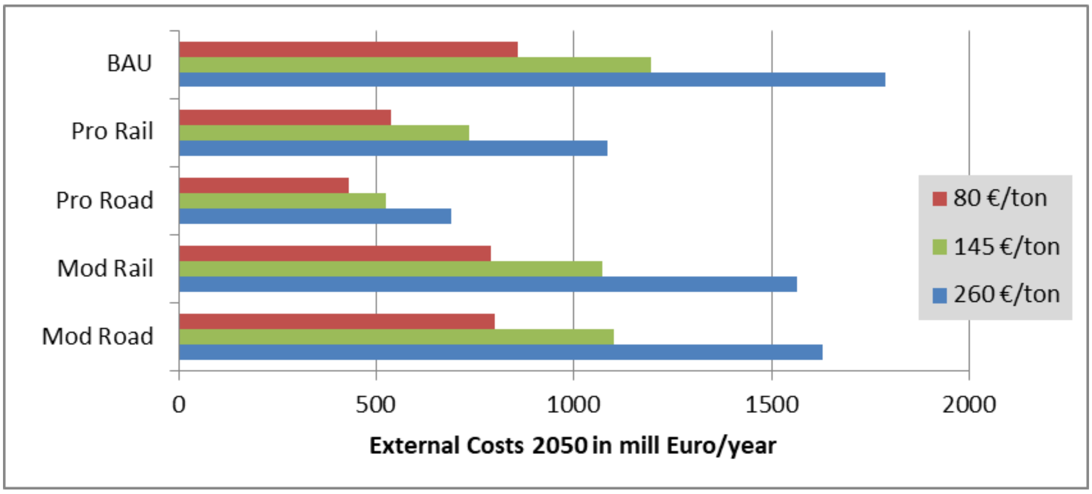
These indicators imply that road electrification and the transformation of the power sector progress as programmed. In case these endeavours fail or slow down the advantage of the Pro Road over the Pro Rail scenario might get less clear.

4.5 Sensitivity Assessments

4.5.1 Variation of Climate Change costs

CO_2 costs increase from 80 Euro/ton in 2015 to 145€ in 2030 and 260€ in 2050. Sensitivity calculations assume constant costs using 2015 and 2030 price levels. The price changes have strong effects on the outcome of the scenarios. However, since effects are comparable for each of the scenarios, the ranking is not changed and conclusions remain stable.

Figure 19: Sensitivity analysis: CO_2 costs on RALP corridor



Source: Fraunhofer ISI

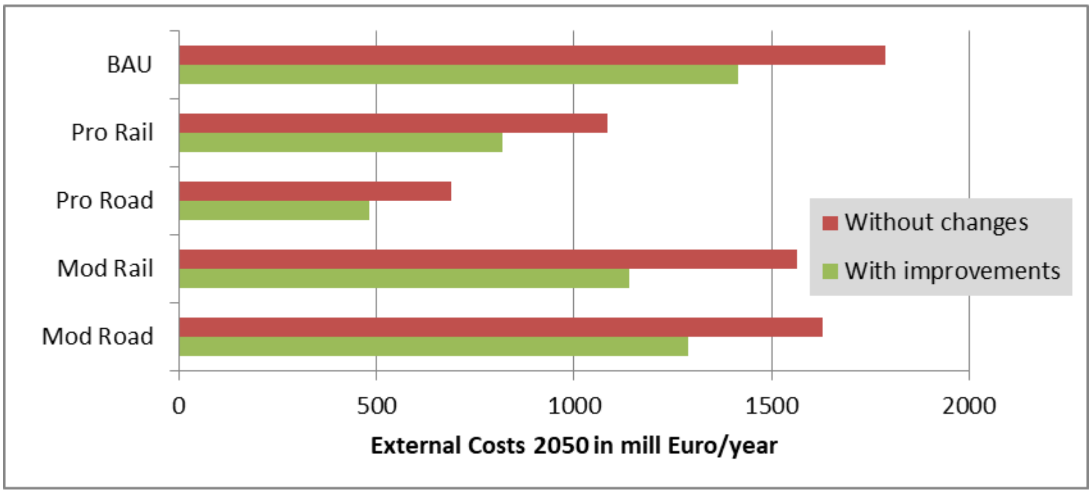
4.5.2 Reduction of emissions from inland water shipping

Inland water shipping makes up a large share of the transport volume, as well as on the external costs. A sensitivity assessment calculates the impacts of reduced pollutant emissions from inland barges on the RALP corridor in the year 2050. Firstly, it is assumed that energy efficiency increases by 1% annually and thus CO_2 emissions will be reduced by 35% in 2050. Additionally, it is assumed that Directive 97/68/EC on non-road mobile machinery (NRMM Directive) that has been implemented in rail transport (see chapter 3.3), will be applied to water transport as well. Through the implementation of scrubbers and filters, the NOx emissions will decline by 88% compared to 2015 levels and $PM_{2.5}$ emissions may be eliminated entirely.

The sensitivity calculations (Figure 20) show that these measures have an enormous effect on the environment with 20-30% reduction in external costs, which implies annual reductions of external costs in the order of 200 to 400 million Euros. Since presently, the inland shipping sector is dominated by small-scale enterprises that operate at their profit limit, major private investments are improbable. However, state support to increase the environmental performance of inland barges might prove to be very cost effective.

If the whole picture is regarded, the ranking of scenarios is not affected by these measures, which implies that the above conclusions are stable even with enormous improvements in water transport.

Figure 20: Sensitivity calculations for improvements in inland water shipping on the RALP corridor 2050



Source: Fraunhofer ISI

5 Discussion and Conclusions

5.1 Scenario results

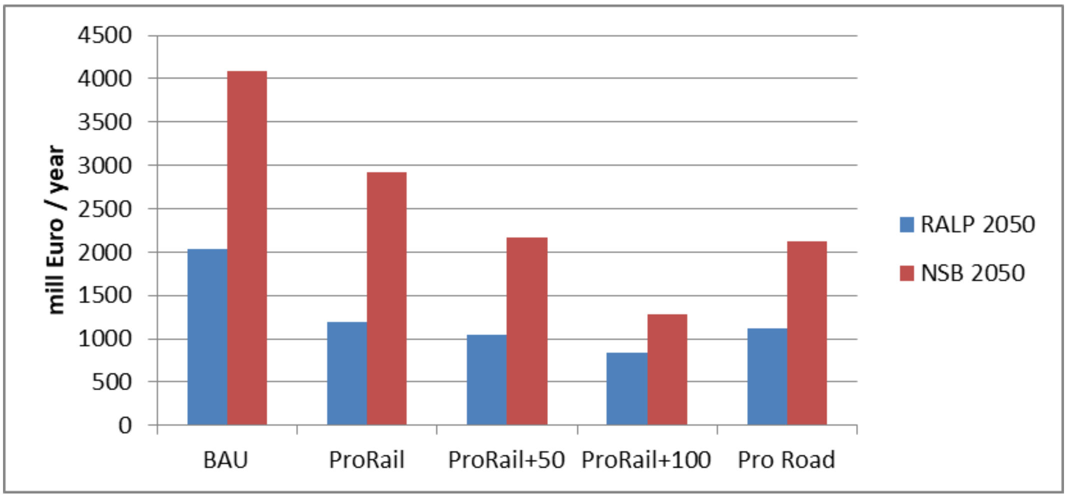
Among the single-mode strategies to combat greenhouse gas emissions in the European freight sector, the road scenarios definitively get closer to a deep cut in GHG emissions. Even though the external costs of rail are close to negligible, the Pro Rail and Mod Rail cases lag behind the performance of the Pro Road and the Mod Road scenarios. The main driver is the electrification of motorways, which is exclusively considered in the road scenarios, while the railways are assumed being fully electrified in the BAU case already. The remaining share of goods transported on trucks and by inland barges then continues causing greenhouse gas emissions and other externalities mainly from fossil fuels.

The mode shift of goods from road to rail is limited. These limits are on one hand determined by physical characteristics of the rail system, and are on the other side given by economic considerations. Along the strong corridors considered in this study, in particular on the Rhine-Alpine-Axis, the economic advantage of road and shipping is not as striking as it is on more peripheral transport relations. Here, the technical barriers to extend capacity in due time and to reasonable costs get more relevant.

Although by 2050, the energy efficiency of railways will approach a physical optimum and their economic attractiveness against road is compelling, improving the transport sector's GHG footprint decisively can only go via the parallel de-carbonising of trucking. Options for bringing down road-based GHG emissions include the sector's electrification through overhead wires, batteries or synthetic fuels.

For understanding the impact of following both pathways simultaneously, a combined scenario for 2050 using the Pro Rail scenario and 50% / 100% electrification of motorways was calculated. A 50% electrification would bring the Pro Rail scenario down to the level of Pro Road, a 100% electrification would reduce external costs to an even lower level than Pro Road (Figure 21).

Figure 21: Total external costs of the combined Pro Rail scenario with motorway electrification on the RALP Corridor

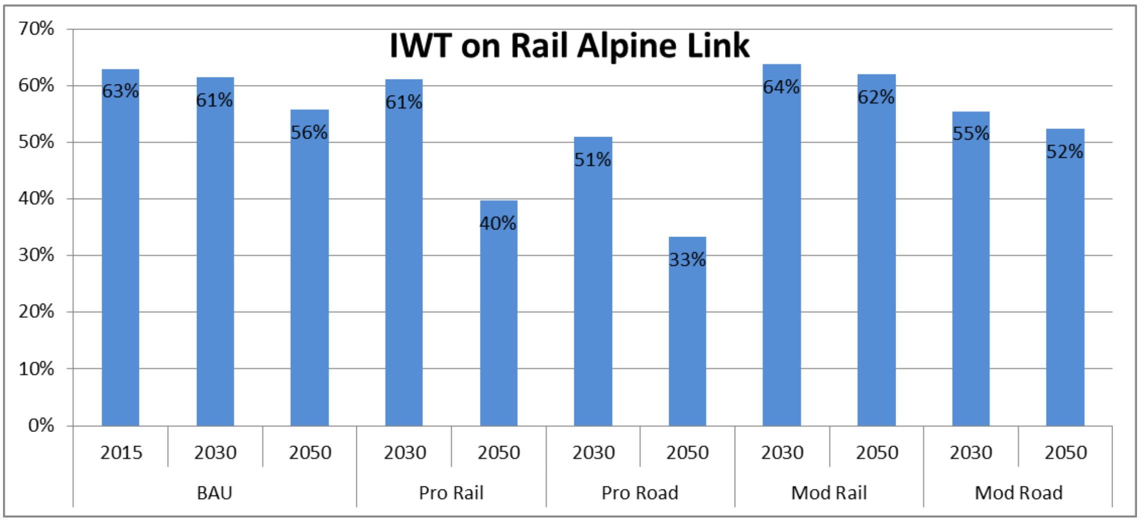


Source: Fraunhofer ISI

Inland waterway transport plays a decisive role in European freight transport and thus must be part of future GHG mitigation strategies. The share of inland barges on the RALP corridor varies considerably between 33% and 64% (Figure 22). These are outputs of the transport model that reacts to the price incentives. Interestingly, the rail scenarios have a larger share of transport on barges, compared to the road scenarios. Pro Road generates the lowest share, while Mod Rail even has a larger share than BAU. Obviously, the price changes assumed in the scenarios provide strong incentives for inland water transport and reduce the rail share along the Rhine to only 6% in Mod Road 2050. This can be (partly) explained by the large share of fuels transported by inland barges that cannot be transferred to other land transport modes[2]. Liquid fuels can instead be distributed by pipelines. For inland barges, further improvements would be necessary to reduce external costs. The latter is not treated in this study.

2 A future decrease in fossil fuels might impact the tank barge sector. However, a large part of this sector is also related to the chemical sector, which is also heavily dependent on oil and oil based products.

Figure 22: Share of Inland Water Transport (tkm)



Source: Fraunhofer ISI

5.2 Methodological considerations

The assessment of sustainability impacts in this paper have built on four major sources of information: (1) the transport scenarios for rail and road, (2) the TPR chain model results (3) emission and cost data for social impacts and (4) cost estimates for implementing the scenarios. These data sources have their merits and weak sides, which we briefly discuss here.

The **transport scenarios** are described in detail in the LowCarb-RFC working papers 5 (BAU and Pro Rail scenarios) and 6 (Pro Road scenario). As climate change mitigation is urgent, these scenarios take a maximum impact perspective. In both modes these will not be easy, if not impossible, to achieve. So this first and decisive corner stone of the sustainability impacts presented here can be questioned. Therefore, the Mod Road and Mod Rail scenarios were introduced as sensitivity cases for a less ambitious development of the sector.

The **TPR Transport Chain Model** was tested with numerous real world cases and in itself is considered a robust tool. While the smaller changes in the Mod Road and Mod Rail scenarios are closer to what we observe between the modes in freight transport today, the massive shifts in the Pro Road and Pro Rail case seem unrealistic at a first look. The comparison of the cases, however, shows that the model identifies tipping points in the modes' cost efficiency, which will also happen in real life. It also needs to be considered that the model assumes no capacity constraints, i.e. it takes as a pre-condition the needed capacities are provided.

Emission and external cost values are provided by valuable methodologies and agreed international data bases. Nevertheless, the estimate of appropriate cost factors is by nature uncertain as we need to deal with various unknown factors and vague statistics. Greatest uncertainties are attached to the costs per ton of carbon dioxide. This global effect causes impacts on all world regions and situations in peoples' lives. Moreover, the impacts change over time. To capture these uncertainties, the paper contains a sensitivity analysis in section 4.5.

Cost data for setting the social impacts into relation is hard to estimate for the profound changes in mode shares as inflicted by the Pro Rail and Pro Road scenarios. Some of the uncertainties have been discussed in Section 4.4. Here it was concluded that the difference between social effects and greenhouse gas costs is so clear with the values selected for this paper, that substantial changes to the cost assumptions would not alter them. But detailed cost considerations are subject to further investigations.

All in all, we consider the results of this paper as robust and clear in its message. Even changes in most of the parameters will still identify road transport at the target for quickest and most decisive de-carbonisation.

5.3 Transferability to local cases

This discussion paper constitutes the 8th out of nine paper produced by the LowCarb-RFC project. What comes next is the application of the scenarios and the assessment method to the local case of North-Rhine-Westphalia. For the sustainability assessment methodology, we can discuss the transferability to NRW along the four methodological corner stones introduced above.

Scenarios: The very macroscopic and extreme view taken in the corridor analyses in the LowCarb-RFC project so far may be too crude for NRW. To get into dialogue with local decision makers scenarios closer to what is discussed in national and European transport planning might be more helpful.

Transport model: Concentrating only on the corridor flows might be less relevant for NRW, although the TPR chain model as specifically listed impact of the corridors on the area. For discussions with decision makers, the corridor approach may be too aggregated and could be replaced by a local transport matrix.

Social cost method: This rather universal method is fully transferable to the NRW case. Its principle is part of the impact assessment of the German Transport

Investment Master Plan BVWP (BMVI 2016) and thus well usable for stakeholder discussions in NRW.

Implementation costs. The approach taken here is rather crude. For NRW more detailed data via the federal and state investment plan are available. These data sources should be used for more accurate indicators on economic impacts, cost efficiencies and GHG mitigation costs.

5.4 Further research

So far the LowCarb-RFC project has identified road transport as the major target for mitigating GHG emissions in freight transport. The project has also defined some steps towards making the railways more supporting by gaining market shares through internal reforms and by applying new business models. However, a lot of issues still remain unresolved. Some of these are:

- **Which of the various ways to de-carbonise long distance trucking is best feasible and most quick?** Overhead-wire trucks seem to be more efficient than producing climate neutral combustion fuels. But does that hold true in case new fuel synthetisation methods appear?
- **What is a feasible European way?** Long distance freight transport is mainly cross-border. Isolated action in single countries could scatter the picture in road transport similarly than it currently is with the railways.
- **Which way to go with local trucking?** This makes around half of all truck kilometres and is thus highly relevant for greenhouse gas emissions in freight transport as well.
- **How to achieve standardisation in transhipment technologies?** There are several powerful systems for efficiently shifting containers and trailers between trucks and trains. But they need to be decently tested, installed and promoted (or skipped) to quickly install an attractive intermodal system for land freight transport.
- **What to do with shipping?** The scenarios have uncovered that, at least along the busy corridors, inland waterway transport plays a major role. Although the sector consists of considerable free capacity, its system disadvantages like speed and network density stop it from taking more market shares. Moreover, the profit margins in shipping are so low that the shippers cannot afford new, efficient and clean barges on their own account. Investment, innovation and funding programmes need to be strengthened to support the sector.

- **Which role is there for completely new transport systems?** With maglev trains, Hyperloop, underground delivery systems like Cargo Sous Terrain or drones new ways of moving goods and people are discussed. If the current transport system fails to adapt to a low carbon future, there might be some charm in going new ways. This might be for single relations or areas or for specific market segments.

Further research at the national and European scale will have to address these questions and deliver action plans. Given the slow pace in which freight transport improves in climate efficiency, the plans need to be pragmatic and feasible in short notice. A decent impact assessment can help prioritising options. Therefore, it needs to cover environmental aspects plus social and economic implications.

High values for the use of natural resource shall be applied, which is consistent to the economic principle of caution. In order to encourage action of public and private entities, an influential impact assessment scheme shall value chances above risks. So besides the techno-organisational challenges listed above, future research should also look into the role and design of impact assessment and decision support schemes.

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LowCarb-RFC Project Publications

The below list of 9 working papers and 3 summary report is in parts preliminary as some of the material is in preparation by the time of releasing this report. A current list of publications is at:

Fraunhofer ISI: LowCarb-RFC project website: https://www.isi.fraunhofer.de/en/competence-center/nachhaltigkeit-infrastruktursysteme/projekte/low-carb_rfc.html.

Stiftung Mercator, Climate-Friendly Freight Transport in Europe: https://www.stiftung-mercator.de/en/project/climate-friendly-freight-transport-in-europe/.

Transport & Environment, Low Carbon Freight: http://lowcarbonfreight.eu/.

<u>Working Papers</u>

Doll, C.; J. Köhler; M. Maibach; W. Schade; S. Mader (2017): The Grand Challenge: Pathways Towards Climate Neutral Freight Corridors. Working Paper 1 of the study LowCarb-RFC - European Rail Freight Corridors going Carbon Neutral, supported by Stiftung Mercator and the European Climate Foundation. Fraunhofer ISI and IML, INFRAS, TPR and M-Five. Karlsruhe.

Petry, C. and M. Maibach (2018): Rail Reforms, Learnings from Other Sectors and New Entrants. Working Paper 2 of the study LowCarb-RFC - European Rail Freight Corridors going Carbon Neutral, supported by Stiftung Mercator and the European Climate Foundation. Infras. Zurich.

Gandenberger, C.; J. Köhler and C. Doll (2018): Institutional and Organisational Change in the German Rail Transport Sector. Working Paper 3 of the study LowCarb-RFC - European Rail Freight Corridors going Carbon Neutral, supported by Stiftung Mercator and the European Climate Foundation. Fraunhofer ISI. Karlsruhe.

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Summary Reports

Petry, C.; M. Maibach; C. Gandenberger; D. Horvat; C. Doll; S. Kenny (2018): Myth or Possibility – Institutional Reforms and Change Management for Mode Shift in ‘Freight Transport. Summary Report 2 of the study LowCarb-RFC - European Rail Freight Corridors going Carbon Neutral, supported by Stiftung Mercator and the European Climate Foundation. Infras, Fraunhofer ISI, T&E. Karlsruhe.

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