EUROPEAN FREIGHT SCENARIOS AND IMPACTS

SUMMARY REPORT 2
EUROPEAN RAIL FREIGHT CORRIDORS FOR EUROPE—STORYLINE AND RESPONSIBILITIES

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EDITORIAL INFORMATION

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CONTENT

1 INTRODUCTION 5

1.1 The LowCarb-RFC Study 5
1.2 Background: climate mitigation in freight transport 5
1.3 Purpose of this report 6

2 THE POTENTIAL FOR A MODAL SHIFT TO RAIL 9

2.1 Drivers of a modal shift 9
2.2 The competitiveness of transport modes today 10
2.3 The business-as-usual scenario 10

3 THE PRO RAIL SCENARIO 15

3.1 The pro rail scenario narrative 15
3.2 Generalised costs in the pro rail scenario 16
3.3 Implementing the pro rail scenario 18

4 DECARBONISING ROAD TRANSPORT 19

4.1 Status quo: trends and challenges 19
4.2 Drivers of a positive road haulage future 19
4.3 Scenario narratives: the pro road vision 21
4.4 Cost and performance assumptions for road haulage to 2050 23
4.5 Conclusions 24

5 MODELLING TRANSPORT IMPACTS 27

5.1 Introduction 27
5.2 Literature review 27
5.3 Method 28
5.4 Data 29
5.5 Main results of the study 30

6 SUSTAINABILITY IMPACT ASSESSMENT 33

6.1 Future developments that will change emissions 33
6.2 Assessing greenhouse gas emissions 34
6.3 External costs 34
6.4 Cost efficiency 38

7 THE FULL PICTURE 41

7.1 The scenarios 41
7.2 Curing road emissions is indispensable 41
7.3 The case for strong railways 41
7.4 The merits of doing both 42
7.5 Underestimated potential of shipping 42
7.6 Climate change and transport externalities 42
7.7 Concluding remarks 43

ABSTRACT

This second summary report of the study LowCarb-RFC presents extreme scenarios for cost cuts in rail freight and for the electrification of road haulage for two European freight corridors by 2050. The scenarios Pro Rail for competitive freight railways and Pro Road for greenhouse gas neutral road transports aim at quantifying the potential contributions of these two respective directions of transport and climate policy to climate protection and sustainability.

Pro Rail drafts a future, in which rail transport costs decline by 66 per cent through regulatory frameworks, entrepreneurial measures and the consequent application of digitalisation and automation. At the same time, road haulage costs increase by 25 per cent through taxes, charges and regulation. In contrast, Pro Road describes a future in which road transport operates carbon neutral through overhead wires, batteries and fuel cells.

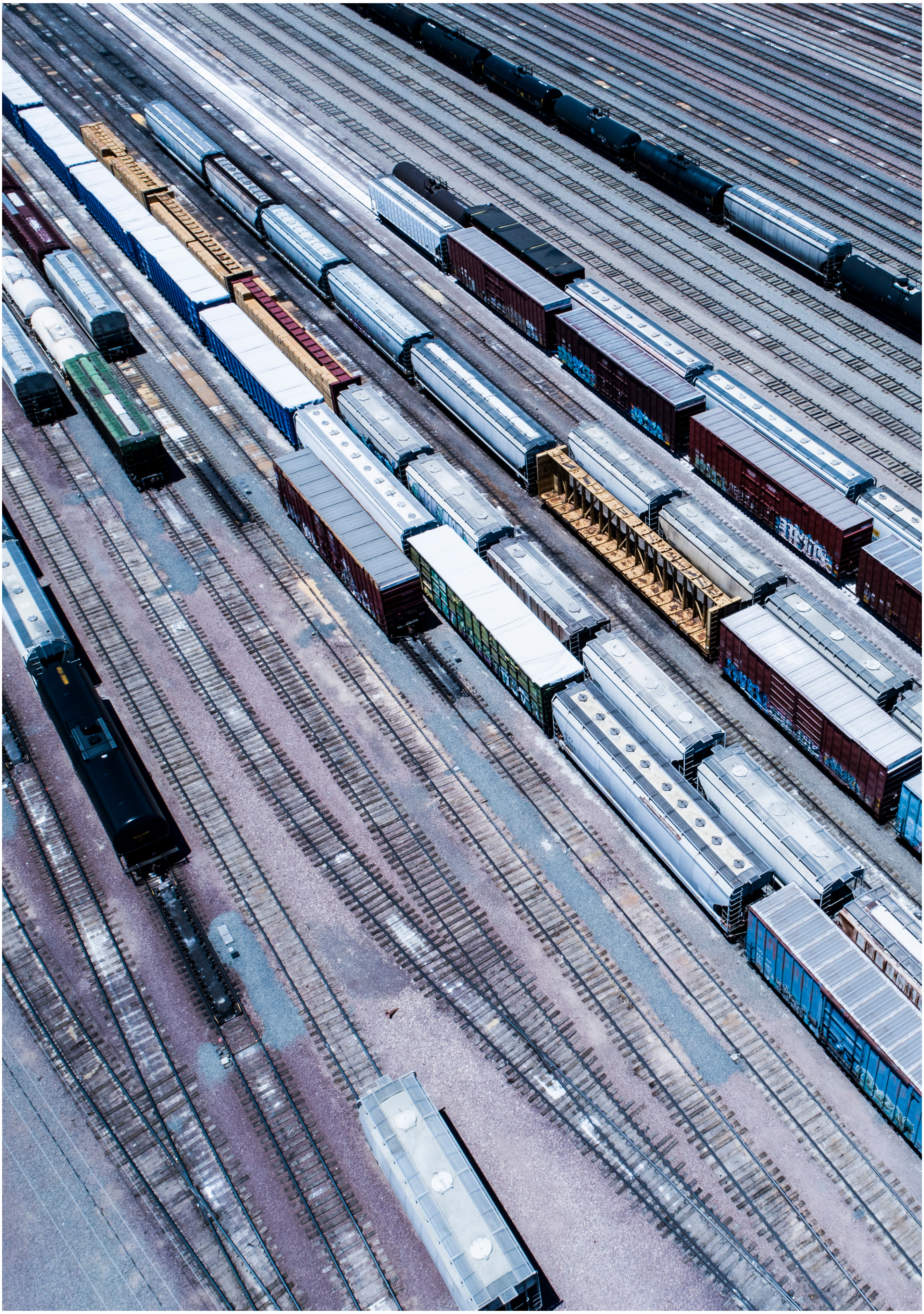
The market share of the railway triples in the Pro Rail scenario against the reference case in the year 2050. This is partly at the expense of trucks, but also at the expense of inland shipping. Along the Rhine-Alpine-Corridor 2050, GHG emissions decline from 60 Mt to 35 Mt CO_2-equivalents in the Pro Rail scenario and to 22 Mt in the Pro Road scenario. Through the combination of both measures, a further reduction to 16 Mt would be feasible. As both of these extreme scenarios are unlikely to be realised, climate policy needs to exploit the full emission reduction potentials in all modes.

ZUSAMMENFASSUNG

Der hier vorliegende zweite Summary Report des Forschungsprojektes LowCarb-RFC stellt weitreichende Szenarien zur Kostenreduktion im Bahnverkehr und zur Elektrifizierung des Straßengüterverkehrs für zwei europäische Korridore bis 2050 vor. Die Szenarien Pro Rail für wettbewerbsfähige Güterbahnen und Pro Road für treibhausgasneutrale Straßentransporte sollen die grundsätzlich möglichen Klima- und Nachhaltigkeitsbeiträge beider Stoßrichtungen der Verkehrspolitik quantifizieren.

Pro Bahn beschreibt eine Zukunft, in welcher die Transportkosten der Bahn durch regulatorische Rahmenbedingungen, betriebliche Maßnahmen sowie die konsequente Anwendung von Vernetzung und Automatisierung um 66 Prozent sinken. Gleichzeitig steigen die Lkw-Kosten durch Steuern und Abgaben um 25 Prozent. Pro Road beschreibt dagegen eine Zukunft, in der durch Oberleitungen, Batterie- und Brennstoffzelle der Lkw CO_2-frei fährt.

Der Marktanteil der Bahn verdreifacht sich im Pro Rail-Szenario gegenüber der Referenz 2050. Dies geht teilweise zu Lasten des Lkw, jedoch auch zu Lasten der Schifffahrt. Auf dem Rhein-Alpen-Korridor 2050 vermindern sich die THG-Emissionen des Güterverkehrs in Pro Rail von 60 Mt auf 35 Mt CO_2-Equivalente und in Pro Road auf 22 Mt. Durch eine Kombination beider Ansätze ließe sich eine weitere Reduktion auf 16 Mt erreichen. Da diese extremen Szenarien kaum umsetzbar sein werden, müssen die Emissionsreduktionspotenziale in allen Verkehrsträgern voll ausgeschöpft werden.



1 INTRODUCTION

1.1 CONTEXT: THE LOW-CARB-RFC STUDY

This publication is one of three summary reports of work performed within the study "Low-Carbon Rail Freight Corridors for Europe" (LowCarb-RFC). The study is co-funded by the Stiftung Mercator and the European Climate Foundation over a three-year period from September 2015 to November 2018 and is carried out by the Fraunhofer Institute for Systems and Innovation Research ISI (Karlsruhe), the Fraunhofer Institute for Material Flow and Logistics 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 because this sector is one of the most steadily growing sources of greenhouse gas emissions in Europe. It is also the most difficult to address by renewable energies and other standard climate mitigation measures in transport. Starting from the classical suite of strategies such as "avoid", "shift" and "improve", the LowCarb-RFC methodology concentrates on the modal shift to rail and on mitigation measures in all freight modes along the two major transport corridors through Germany: the Rhine-Alpine (RALP) corridor from the Benelux countries to Northern Italy, and the North Sea-Baltic (NSB) corridor from Benelux via Poland to the Baltic States. Besides major European strategies, the project considers the implications for transport policy at the intersection of these two corridors in the German federal state of North Rhine-Westphalia (NRW). The project focuses on rail as a readily available alternative to transport large quantities of goods along busy routes using electric power in a potentially carbon-neutral way. Within this setting, the project pursues three streams of investigation:

- **Stream 1: Railway Reforms**. This section of the LowCarb-RFC project explores rail freight as a major pillar of climate mitigation policy. It considers the current slow pace of climate mitigation in the freight transport sector in general and asks how regulatory frameworks, company change management processes or new business models could accelerate it.

- **Stream 2: European Scenarios and Impacts**. Cost and quality scenarios are established for rail, road and waterway transport along the two corridors, and their impacts on the modal split, investment needs and sustainability are modelled. This stream forms the analytical core of the study and provides the basis for the subsequent analysis of intervention pathways.

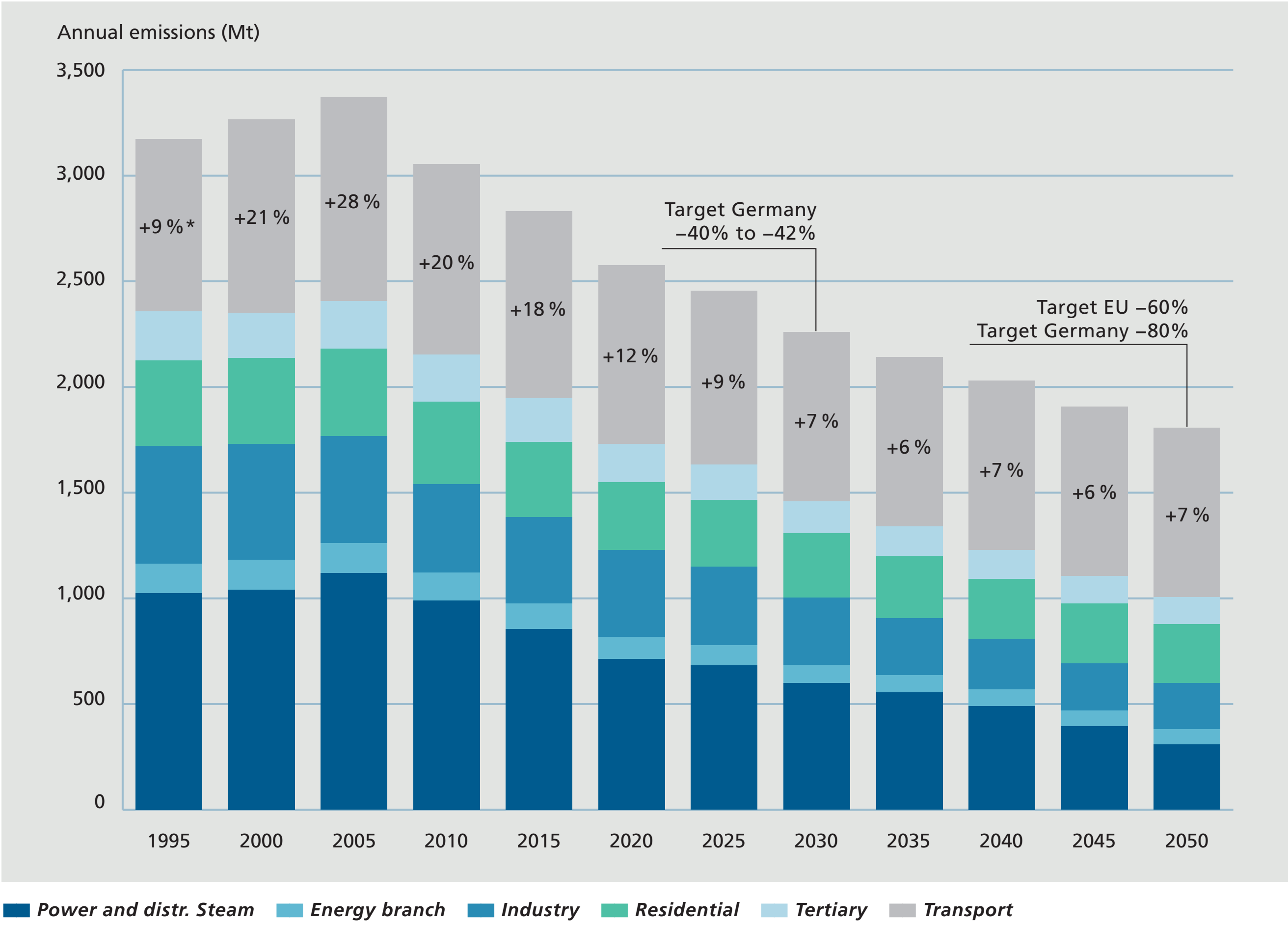
- **Stream 3: Case Study NRW**. This step analyses the transport scenarios and intervention pathways at the level of the local conditions in NRW and looks at the implications for investments or disinvestments in infrastructures, jobs, economic prosperity and the environment.

1.2 BACKGROUND: CLIMATE MITIGATION IN FREIGHT TRANSPORT

Human contribution to climate change is among the biggest foreseeable threats to the environment and our civilisation. Transport, excluding international aviation and maritime shipping, produced 21 per cent of European GHG emissions in 2015 and was 23 per cent above 1990 levels. In freight transport, 72 per cent of GHG emissions were from road transport, where the average emissions from light vehicles actually declined due to improved fuel consumption standards and less carbon-intensive fuels. Only the emissions from truck transport have remained constant. Against this background, it is most likely that we will fail to meet the 40 per cent GHG reduction targets for 2030 compared to 1990 levels across all economic sectors. Largely due to transport, agriculture and other carbon-intensive economic branches, a reduction of only 10 per cent might be realised.

The European Commission's energy model PRIMES projects a total drop in GHG energy-related emissions of 32.9 per cent by 2030 in its reference scenario for EU15 countries compared to 2005. Per annum, the model predicts a 2.7 per cent improvement in the carbon emissions per unit of gross domestic product (GDP), almost half of which is offset by the growth in GDP.

FIGURE 1: Development and projection of energy-related GHG emissions in Europe 1995 to 2050



***% = total transport sector GHG emissions relative to 1990, Source:** *Fraunhofer ISI with PRIMES figures*

A reduction of only 17 per cent is projected for transport by 2030 with respect to 1995, excluding aviation and motion electricity. Alternative estimates arrive at different values. Model calculations for the German Mobility and Fuels Strategy II forecast only 10 per cent reduction of GHG emissions in 2030 compared to 1990. As a result, even though the transport sector is already the sector contributing the least towards mitigation targets in PRIMES, we have reason to consider even this potential overly optimistic.

1.3 PURPOSE OF THIS REPORT

This publication reviews Stream 2 of the LowCarb-RFC study. This covers the development of freight demand scenarios along the Rhine-Alpine and the North Sea-Baltic core network corridors for the years 2030 and 2050, generalised cost scenarios for the railways and road haulage, the assessment of their impacts on transport flows and their sustainability effects. The scenarios depart from the common assumption that the power sector will be 95 per cent decarbonised by 2050 and that all technological and organisational options in the transport sectors are activated in order to either shift goods to rail or to avoid greenhouse gas (GHG) emissions in road haulage as much as possible. To this extent, the LowCarb-RFC scenarios reflect extreme cases for improving rail's competitiveness and for decarbonising road transport.

We consider these extreme cases to be indispensable elements of a transport policy that respects the intergovernmental conclusions reached at the UN's climate conference COP 21 in November 2016 in Paris. Soft and voluntary measures for climate mitigation have not worked to date. By 2030, model calculations indicate that we will have reduced GHG emissions in European transport by only 10 per cent although a 40 per cent reduction was agreed by the EU and some member states, including Germany. Against this background, this summary report shows the potentials and impacts of two specific policies: shift to rail or electrify road. However, these policies are not mutually exclusive. The report also shows the merits of doing both in an additional exercise. The study also investigates what happens if we implement the scenarios in a half-hearted way.

We formulate potential futures for the European freight transport sector using the following scenarios:

- **Business-as-Usual (BAU):** This reference scenario assumes that the present economic, technological and organisational trends in the transport sectors continue until 2050. These trends include cost cuts and efficiency gains in the rail and inland waterway (IWT) sector, moderate energy price increases, labour market trends, ongoing moderate automation, etc. The assumptions made in the BAU case are non-disruptive and slightly biased towards rail and IWT. Accordingly, the outcome should be broadly in line with current transport market projections with a focus on sustainability.

- **Pro Rail:** This scenario portrays comprehensive modernisation and improved efficiency in the European rail freight market. All the conceivable technologies and organisational structures that enhance quality and efficiency are fully exploited. This may imply a complete reconstruction of the rail freight business compared to the sector's current structure, at least along the major corridors. What remains is the concept of electric trains on tracks. Full digitalisation and automation of infrastructures, rolling stock and operations, active marketing and new forms of cooperation and business models will drive down the railways' unit costs considerably. At the same time, trucking will be subject to additional sustainability charges, new road construction will come nearly to a halt, the labour market remains restrictive and autonomous driving is restricted. The Pro Rail scenario describes a future in which all the options for strengthening and modernising the rail freight sector along the major corridors are fully realised. Realising such profound cuts in costs and improvements in infrastructure availability and service levels requires fundamental changes in organisational structures, policy priorities and business models. The scenarios do not specify who the new players are in European rail freight transport and what the disruptive business models for the sector might look like.

- **Pro Road:** Rail-sceptic voices argue for increased investments in road freight, because this could reduce greenhouse gas emissions more quickly and cheaply than expensive modal shifts to rail or inland waterways. The basic narrative of a Pro Road vision builds on the argument that road haulage can become at least as clean as rail (zero exhaust emissions), fully decarbonised (zero CO_2), reliable (little congestion) and safe (zero accidents). Furthermore, negative factors like the lack of drivers can be remedied and road haulage can further reduce its costs (due to larger vehicles and digitalisation) and increase its efficiency (due to digitalisation and improved cooperation). In such a world, road freight would clearly triumph over rail freight, simply because many of the arguments in favour of rail (safety and certain environmental aspects) disappear, while arguments in favour of road (like costs and flexibility) are extended or at least maintained.

- **Mod Rail and Mod Road Scenarios:** The assumptions made in the Pro Rail and Pro Road scenarios are at the extreme ends of what might happen in the freight transport sector. This is very different to the pace of change observed in the past. To investigate how the transport system reacts if we cut the extreme efficiency gains and technical implementations by half in each case, we also defined two "moderate" scenarios: Mod Rail and Mod Road. The term "moderate", however, is only used relative to the Pro scenarios; these moderate scenarios also contain massive cost reductions and technical changes compared to today's situation in rail, road and IWT.

Summary Report 1 (Petry et al. 2018) of the LowCarb-RFC project discusses the options for and the difficulties with structural reforms of such dimensions in large organisations. Bearing this in mind, the Pro Rail scenario drafted here is to be understood more as a target for a roadmapping process in the freight transport sector than as the outline of a likely future. While we are fully aware that the Pro Rail scenario is unrealistic, the LowCarb-RFC study explores the limits of how much rail can contribute to achieving the –60 per cent GHG reduction target for transport in 2050 compared to 2005 levels as postulated by the EC Transport White Paper of 2011.

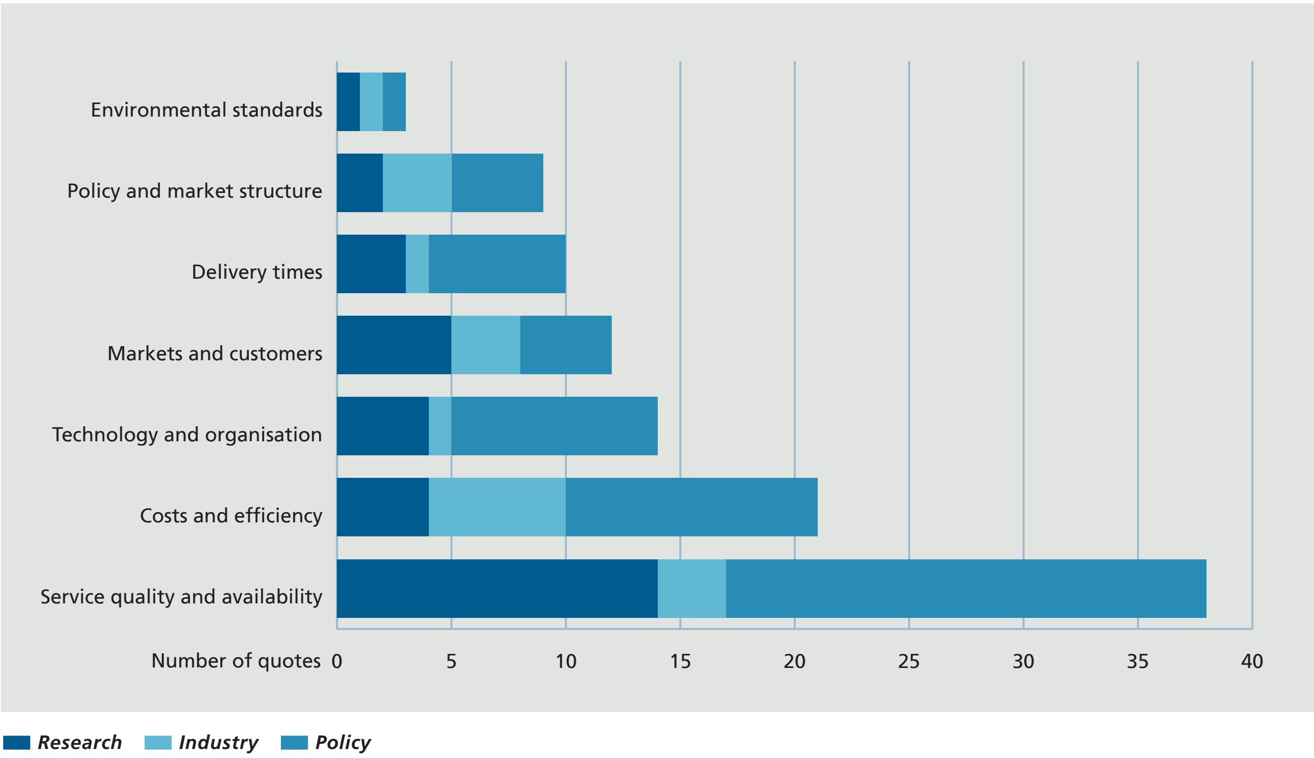
2 THE POTENTIAL FOR A MODAL SHIFT TO RAIL

2.1 DRIVERS OF A MODAL SHIFT

In working paper 5 of the LowCarb-RFC study (Doll and Köhler 2018), we reviewed the main drivers of a modal shift in freight transport along two of the major European rail freight corridors: RFC1: Rotterdam-Genoa and the western part of RTC8: Antwerp-Warsaw. Key publications for the review include the German railway's strategy "Zukunft Bahn" (Deutsche Bahn 2015), the EC core network studies on the Rhine-Alpine (EC 2014), North Sea-Baltic (Wojciechowski 2016) and Scandinavian-Mediterranean corridors (Trautmann 2016), the CERRE policy papers (Crozet et al. 2014), the EC-funded studies BESTFACT (Permala and Eckhardt 2015) and PLATINA II (Lambrechts and Dasburg-Tromp 2014), the CE Delft and TRT study on modal shift drivers (De Boer et al. 2011) and the studies Rail Network 2030 (Holzhey 2010) and Financing Sustainable Rail Transport (Sutter et al. 2016) conducted for the German Federal Environment Agency (UBA). Institutional reports from ERRAC, ITF, the Network of European Railways (NEE), CER and other institutions have also been reviewed. A detailed compilation of the studies is available in LowCarb-RFC Working Paper 5 (Doll and Köhler 2018).

From 19 literature sources, we extracted 66 individual statements on the drivers for and barriers to a modal shift to rail. We grouped these statements into eight categories that can be ranked in descending order according to the mentioned frequency of the drivers as depicted in Figure 2. The statements were also assigned to one of three stakeholder groups: (1) research community, (2) railways and rail manufacturing industries and (3) policy and civil society organisations.

FIGURE 2: Bibliometric assessment of modal shift drivers by type of study



Source: *Fraunhofer ISI*

The seven groups of drivers can be divided into primary and secondary drivers. Primary drivers are directly visible to customers and include quality, price and delivery times. Secondary drivers, such as technology and market structures, determine primary drivers and are internal to the rail production system. They are highly relevant because new technologies and organisational structures together with supportive policy packages are indispensable for improving the railways' competitiveness.

2.2 THE COMPETITIVENESS OF TRANSPORT MODES TODAY

We construct scenarios on the potential competitiveness of transport modes based on the concept of generalised costs because quality and prices are the two decisive elements determining whether shippers send consignments by road, rail or inland waterway transport (IWT). This concept translates the main quality features of shipping alternatives along the entire transport chain, i.e. from door to door, into market prices. These are then added to the actual freight rates in order to obtain a single virtual cost value.

For the financial part of the generalised costs, we assume that changes in the transport operators' cost burden translate directly into freight rates to their customers. This assumption does not comply fully with observations in the freight sector over the past decades. While decreases in taxes or infrastructure charges in the railways have not translated directly into freight rates, motorway charge increases have mostly been passed along to hauliers' clients. For the 2030 and 2050 scenarios, we ignore such market forces and assume transparent pricing structures. Second, for the non-financial part of generalised costs, we concentrate on delivery and delay times. We do so implicitly because the interrelationship between network saturation, travel speeds and delays is complex, for railways in particular, and depends on several operational standards and infrastructure configurations.

In this study, we reviewed detailed cost items of road, rail, barge and intermodal transport with generalised, bulk and containerised cargo. 2015 cost structures were analysed for the cost categories infrastructure, vehicles, energy, labour and administration. This cost structure forms the basis for later forecasts towards 2030 and 2050 in various scenarios. We consider five cost categories: infrastructure, rolling stock, energy, staff, and overhead costs. Figure 3 shows these by mode of transport for a typical 300 km shipment in continental Europe. While rail is dominated by locomotive- and wagon-related costs, road hauliers' expenses focus on drivers and fuel. In combined transport, transhipment costs add 10 per cent to the cost structure, which needs to be offset by efficiency gains elsewhere in the transport chain to make the service attractive. Parts of these costs are fixed per shipment, others are variable by distance or variable by time. In single wagonload rail transport, the fixed costs make up about 36 per cent of the total costs for a 500 km shipment. For road haulage, no fixed costs were considered for loading and unloading.

For absolute freight rates, we consulted data from the Flemish freight model (Flemish Traffic Centre 2017). Together with road haulage costs from the cost information system of the German Federal Association for Road Haulage, Logistics and Disposal (BGL 2017), we derived the cost structure depicted in Figure 4. The data suggest that block trains are completely competitive with trucking, while container trains are about equal and single wagonloads cannot compete in terms of costs. The large differences in rail costs per ton-kilometre are caused by different load factors, i.e. the number of tons per train. The overall load factor in rail transport results from the tons per loaded wagon, the share of empty wagons in the network, and the length of trains in wagons per locomotive. The same factors are relevant for truck and barge transport with the exception of train length.

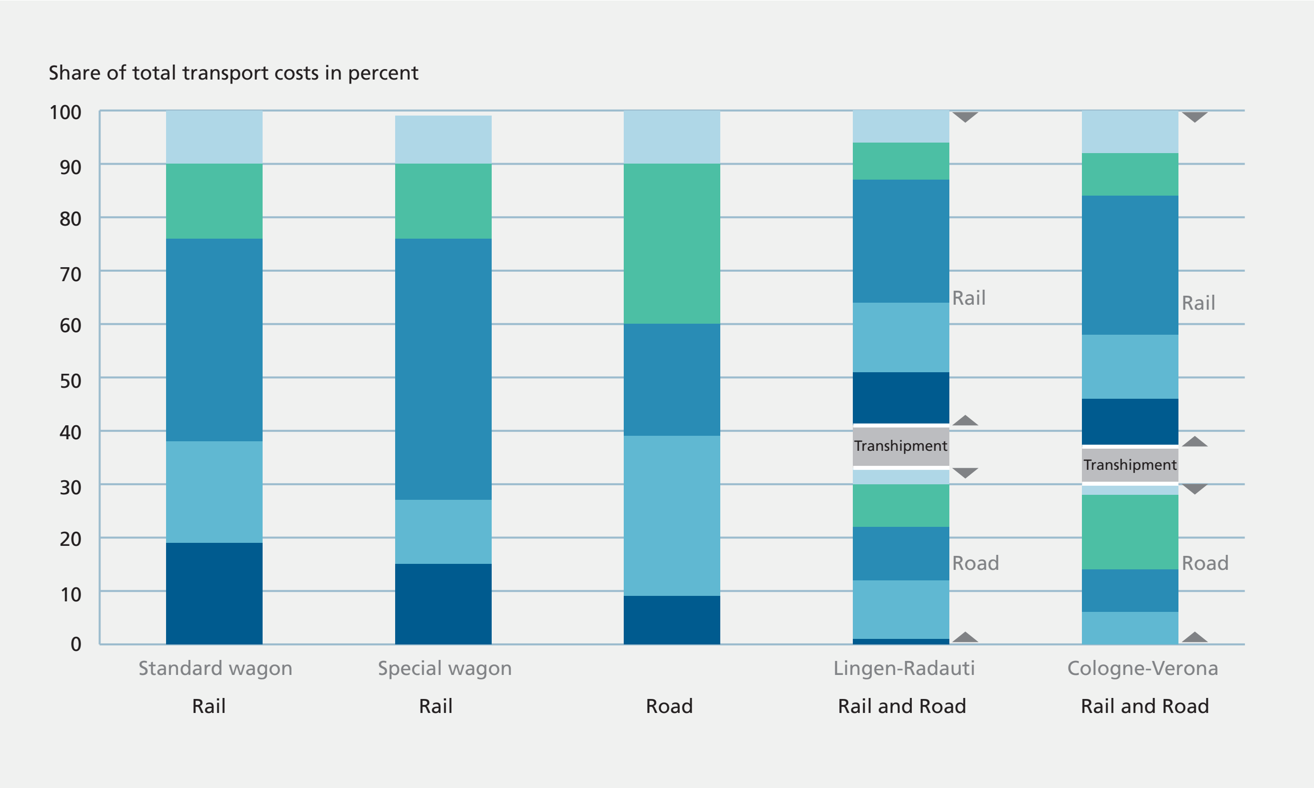
The weight of goods per wagon, truck or vessel depends on the current consignment and the type of cargo: there are weight-sensitive bulk goods and space-sensitive consumer goods. The share of empty wagons is close to 50 per cent, while the share of empty trailers in road haulage ranges around 20 per cent in Western Europe. The length of trains is restricted to between 650 m and 740 m in Europe. Container and bulk trains are usually this long, while single wagonload trains are often much shorter.

2.3 THE BUSINESS-AS-USUAL SCENARIO

The BAU scenario adheres to current policy and business plans and retains the transport systems as they are at present until the mid-21st century. In the BAU scenario, we do not consider major technological or organisational innovations disrupting long-distance freight transport—even though some potentially disruptive trends can already be identified: automation, platform-based demand and supply management and the electrification of road transport.

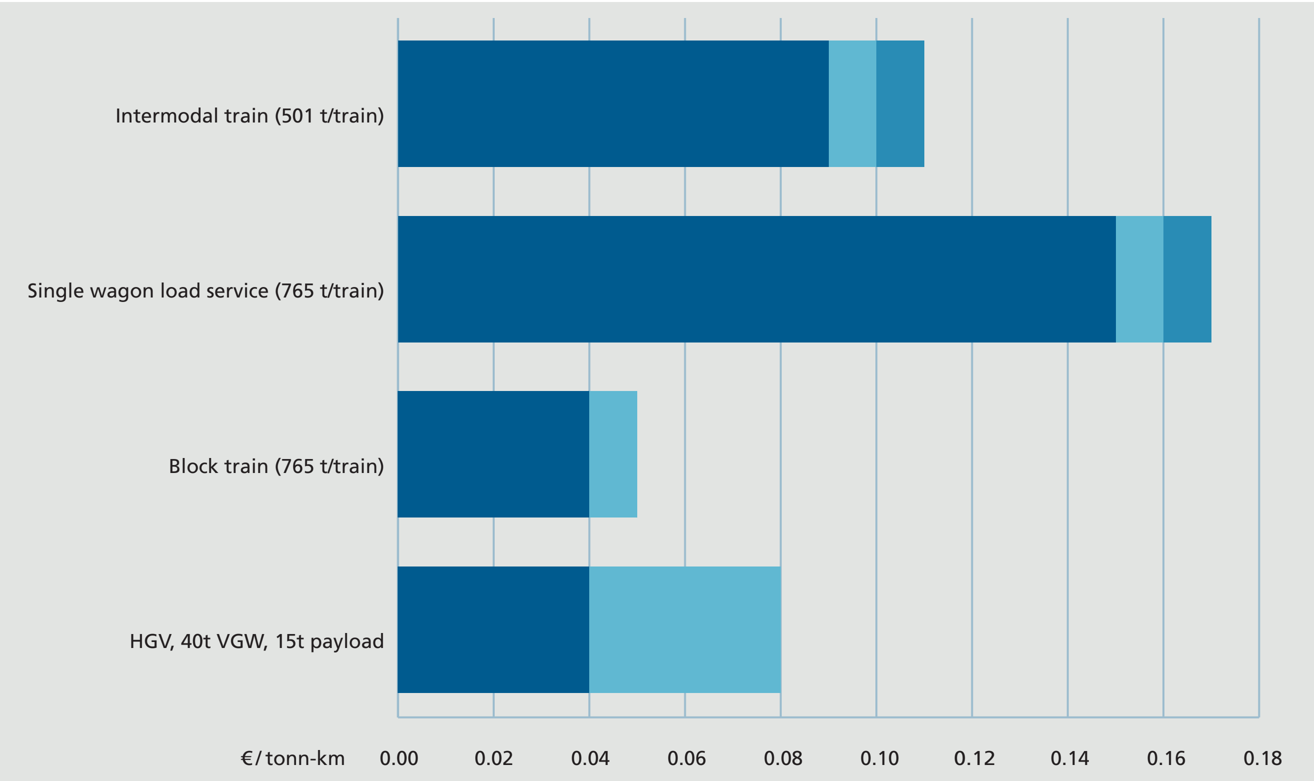
The BAU scenario describes a state in which European and national freight transport policy remain more or less the same as they were in 2015. Planned infrastructure projects like the Iron Rhine will be completed and all modes retain sufficient capacity to keep their 2015 modal share through small to medium capacity investments. Efficiency improvements are more continuous and somewhat faster in rail transport than in road

FIGURE 3: Average share of cost categories in rail, road and combined road-rail transport in Europe, 2015



Infrastructure charges ***Fuel and electricity incl. taxes*** ***Vechicle capital and running costs*** ***Driving personnel incl. social costs*** ***Management and overhead costs; Source****: Fraunhofer ISI with data from HWH (2015)*

FIGURE 4: Comparison of freight rates by mode and service categories, example for a 600 km relation



Time costs ***Distance costs*** ***Transhipment***

Source*: Fraunhofer ISI with data from Flemish Traffic Centre (2017) and BGL (2017)* haulage due to moderate reform processes in railway undertakings. Rail freight can therefore already improve some of the competitive disadvantages experienced in the past in the BAU scenario towards 2050.

The *2030 and 2050 forecasts* are based on transport sector statements, an in-depth literature review and simulation model applications. The relevant transport and energy forecast models are the European tools PRIMES (E3MLab/AUTH 2014) and ASTRA (Doll et al. 2016). These sources are used to predict the generalised costs of rail, road and waterborne transport, as well as their load rates. Load rates (or load factors) in freight transport play a decisive role for final transport prices as high load factors help to distribute fixed costs across more ton-kilometres and make better use of otherwise unutilised capacity. Load factors ultimately express quality issues, since we can assume higher quality results in higher demand for a particular service.

The assumptions in this scenario can be split into general assumptions for 2030 and 2050, which hold true for all scenarios, and assumptions, which are specific to the BAU case. The general assumptions can be summarised as follows:

- Demand projections by mode and country are derived from the PRIMES reference scenario (Möst 2017), but are adapted to the EC studies for the Rhine-Alpine (Wojciechowski 2016) and the North Sea-Baltic (Trautmann 2016) corridors. These already show the largest growth for rail (+43 per cent), followed by road haulage (+35 per cent) and IWT (+28 per cent).

- The digital industry concept is assumed to entirely reshape the means of industrial production. New trends include real gross value added generated by companies through new product lines, the cooperation between employees and robots, the design of supply chains or the relocation of production facilities from low-wage countries back to Europe.

- Energy market policies related to electricity production remain constant for all scenarios. According to the European Commission's Low Carbon Roadmap of 2011, all the economic sectors in the EU are to reduce their GHG emissions by around 80 per cent by 2050 compared to 1990 levels (UIC and IEA 2016). For the electricity sector, we use the 95 per cent mitigation scenarios supported by the German Federal Environment Agency (Öko-Institut and Fraunhofer ISI 2015).

The specific scenario assumptions for the BAU case and the resulting cost reduction rates by 2050 relative to 2015 are briefly described in Table 1. More details and the reductions for the intermediate year 2030 and for the three categories of goods —unitised, bulk and containerised cargo—are described in the LowCarb-RFC Working Paper 5 (Doll and Köhler 2018).

We see considerable cost efficiency gains towards 2050 along the corridors in the BAU scenario already, which are bigger for rail (−18 per cent) than for road (−13 per cent) or for IWT (−8 per cent). This assumption is based on current observations of the successes in re-structuring the sector. There are still enormous efficiency potentials on the railway market, some of which will be tapped by measures that have already been implemented today. These include public subsidies, opening markets, 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 shift away from fossil fuels. While road freight rates are expected to decrease by 17 per cent towards 2050, its relative cost advantage over rail is still 26 per cent.

TABLE 1: Specific assumptions and cost reduction potentials in the BAU scenario

Cost category	Railways	Road haulage
Load factors	Corridor extension to 740m trains; European wagon management and cargo trading platforms **+45 %**	Without longer trucks, only slight improvement possible in loaded hauls and use of truckload space **+10 %**
Infrastructure	Policy plans: halving rail track access charges **–20 %**	No major change to current pricing practices on European motorways **±0 %**
Rolling stock	Soft removal of regulatory barriers but additional administrative hurdles; better management of wagon fleet **–25 %**	Stop trials with longer and heavier vehicles; some field tests with electrified motorways; more expensive trucks (+20 per cent), constant maintenance costs **+9 %**
Energy costs	Full electrification (–10 per cent primary energy demand) and improved energy efficiency through driver assistance (–5 per cent) **–12 %**	Modest improvement in logistics planning, better aerodynamics (–21 per cent), driver-assistance systems **–26 %**
Labour costs	More or less stable for drivers; decrease for local workers due to automation of terminals and track works **–20 %**	Competition for truck drivers by higher wages and stronger enforcement of social legislation (driving and rest times, etc.) drives personnel costs up **±0 %**
Administrative costs	Productivity increases mainly in administrative structures (+25 %); some extra management costs **–25 %**	Advanced use of IT technologies and networking (–20 %); formation of larger haulage companies **–20 %**
Total generalised costs	Dominant drivers: rolling stock and energy costs **–25 %**	Dominant drivers: driver and fuel costs **–19 %**

***Source**: Fraunhofer ISI*

3 THE PRO RAIL SCENARIO

So far, standard measures to improve the market shares of rail freight and the freight sector's energy and climate footprint have failed. Therefore, we explore two extreme options for cutting greenhouse gas emissions on busy European transport corridors in addition to the BAU case: massive shifts to rail and a decarbonisation of trucking. This chapter examines the first option by elaborating a scenario that vastly improves rail freight competitiveness.

3.1 THE PRO RAIL SCENARIO NARRATIVE

Pro Rail constitutes an extreme vision for European freight markets along the major transport corridors. Under external pressure from markets and policy, the railways exploit every possible measure to improve their efficiency and gain market shares. This includes consistent digitalisation, automation, cooperative business models and proactive customer relations. As markets grow and the role of ICT becomes even more important, new players will continue to enter the railway business. These might be global technology or retail companies, or investors from financial or production sectors. Railway infrastructures may or may not be transferred from national to European responsibility, but in any case, we will see a trans-national train control facility similar to Eurocontrol with its national subsidiaries for air traffic management.

Outside the transport sector, the Pro Rail scenario is based on the following narrative:

- Policy: Euro-scepticism will most likely still exist, but pressure from the production industry for more competitive and reliable transport alternatives will force national governments into cooperating more closely to open up and support the railway market and remove national protectionist policies. In road transport, there is a stop to trials that relax truck weight and size limits, and to the electrification of motorways at European level.

- Under the Pro Rail regime, we assume massive support programmes for niche markets, new players and alternative technologies in the rail sector. Field tests allow progressive transhipment, loading / unloading, wagon coupling and train formation technologies to demonstrate their efficiency potentials and scalability. Digitalisation, automation and customer orientation will be integral parts of national and European investment plans stocked with dedicated funds for their implementation and enforcement. Open market regimes will give new players the chance to thrive in the fields of rail equipment provision or rail transport services.

- By 2050, we assume all transport infrastructures are subject to a single pricing structure. Prices are based on social costs, i.e. the preference of citizens for a particular state of the environment they live in. This has implications for all modes: road, rail and inland waterway transport.

- To cater for the additional demand for rail expected in the Pro Rail scenario, we assume that the annual investments in rail projects and network rehabilitation (passenger and freight) increase by 50 per cent between now and 2050. Accordingly, rail dominates the investment activities in transport networks of the EU and the member states. Most rail investments are in extra capacity, the development and full rollout of the European Train Control System (ETCS) Level 3 and preparing the network for longer and heavier trains with a common loading gauge along all corridors and relevant access routes.

- All freight trains can operate completely autonomously. Locomotives and wagons are connected to the internet for full control of functionality, cargo conditions, remote positioning, etc. Wagons are equipped with automated coupling and transhipment terminals can handle the transfer of containers from truck to train and vice versa 24/7 without large crews. Maintenance and servicing of locomotives and wagons (as well as infrastructures) reduce downtimes and costs.

- Diesel as a locomotive fuel is phased out by 2050. Large parts of the network are electrified, including access lines to the major corridors with medium relevance. Hybrid locomotives operating with a pantograph plus battery or fuel cell propulsion serve all non-electrified routes or sections.

The *Pro Rail* scenario is characterised by massive investments in rail capacity in the form of new infrastructure, but more importantly in high capacity and flexible train control and communication systems like ETCS/ERTMS level 3. The estimated amount invested ranges around five to seven billion euros for the period 2015 to 2050 for each of the corridors on top of current expenditures. With advanced asset and demand management, platforms, trains, wagons and container spaces are utilised close to system saturation. These measures lead to a 59 per cent decline in the rail costs per ton-kilometre for general cargo by 2050.

3.2 GENERALISED COSTS IN THE PRO RAIL SCENARIO

Truck operations in the Pro Rail scenario are limited to some extent and subject to stricter social rules and much higher road charges. In total, truck operating costs are expected to increase by 27 per cent by 2050 relative to 2015. This means the relative cost advantage of rail further improves to 81 per cent. We assume the following generalised cost development for the five cost categories:

- **Infrastructure:** We apply two different philosophies concerning the pricing and financing of rail and road transport infrastructures. Figure 5 and Figure 6 show the current average tariffs for HGVs and freight trains in several countries as a reference. For the railways, we assume that the German plans to halve track access charges for freight trains are rolled out to all corridor countries by 2030 and are then extended to a marginal cost-based pricing system following the Scandinavian model by 2050. This strategy implies that funding needs to come from other sources, since we assume massive growth in rail demand. To close the funding gap, we follow the Swiss and Austrian models of cross-funding rail by imposing high surcharges on motorway user tariffs for HGVs.

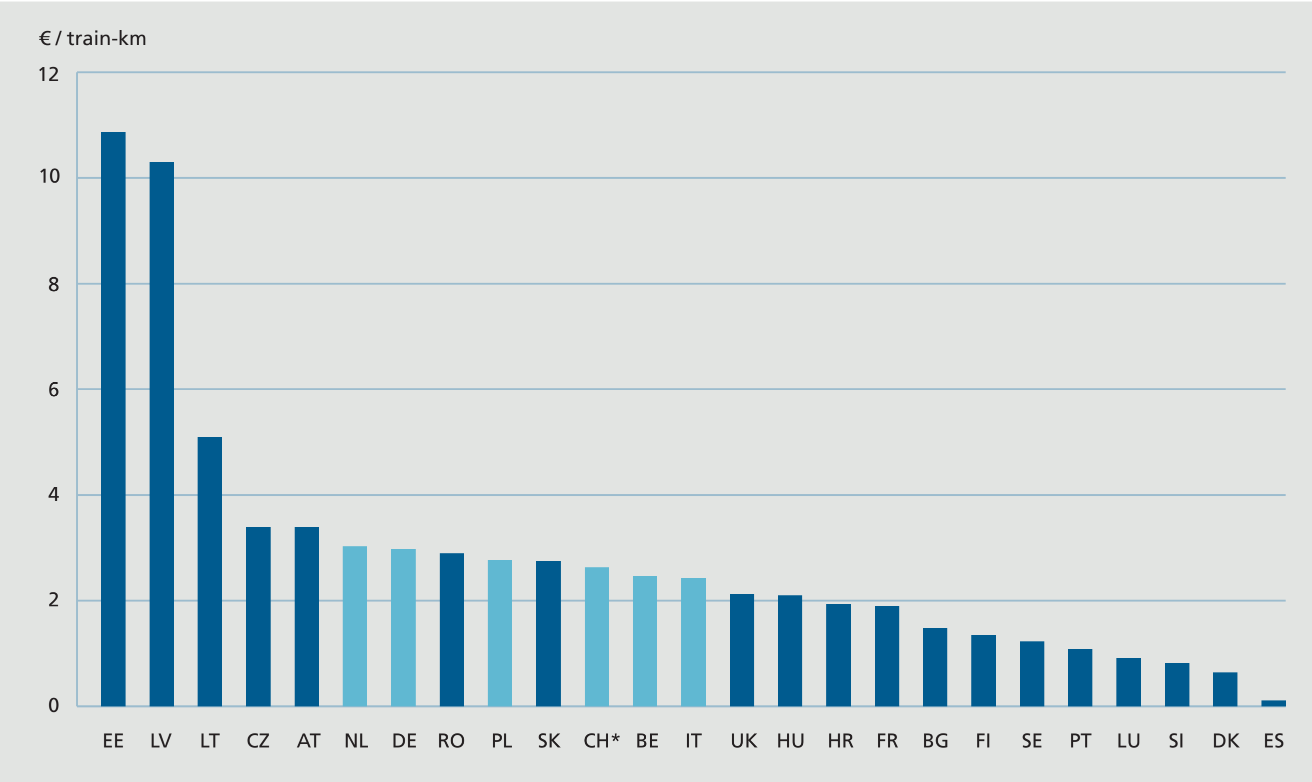
- **Rolling stock:** Currently, the costs of locomotives comprise 64 per cent of regular rolling stock costs or 24 per cent of total rail freight operating costs. Purchase and operating costs are thus a decisive parameter for railway competitiveness. For rail, we assume the full establishment of a European Railway Area with widely de-regulated and/or unified technical and operational standards. The long and expensive licencing process of rolling stock is significantly reduced and train journeys can be booked and managed instantly across Europe on a single customer interface. Expensive special purpose wagons are replaced by modular systems and a Europe-wide wagon management system increases their utilisation and annual kilometres drastically. We assume cost impacts of –60 per cent for locomotives and wagons. For trucking, we consider stricter environmental and safety features for vehicles, diverse and more complex engines (+30 per cent).

- **Energy:** Three elements contribute to the development of energy costs over time: energy efficiency, the energy mix and energy prices by source. While electricity prices have risen steadily, diesel prices rose and fell sharply in the past decade. Railway-specific energy consumption dropped by 19.6 per cent for passenger services and by 22.3 per cent for freight services between 1990 and 2013 (UIC and IEA 2016). Compared to the rather conservative assumptions in the BAU scenario, we assume that innovations to improve energy efficiency in rail transport are successful in the Pro Rail case: These increase the energy efficiency of engines by 15 per cent by 2050 through consistent energy recuperation and engine control, and achieve additional savings of 20 per cent through predictive and automated driving and aerodynamics. The Pro Rail scenario makes the same assumptions about truck efficiency as in the BAU case.

- **Labour:** Due to massive investments in automation technologies and international industry standards, we see a drastic increase in labour productivity in the rail sector. The additional customer services provided and a strengthened bargaining position of labour unions will offset this increase to some extent, but there is still an average annual productivity increase in labour costs of 1.5 per cent. This trend results in labour costs that are 25 per cent lower in 2030 and 68 per cent lower by 2050. In trucking, we see strict control of automation technologies, which reduces potential efficiency gains to 15 per cent. At the same time, labour rates will rise sharply as social standards, wage dumping and certifications will be controlled effectively, and more driver training will be necessary. All of these factors together will mean that labour costs in road haulage rise by 5 per cent in 2030 and by 10 per cent in 2050 rather than decline.

- **Management:** We assume that administrative costs could be cut by 70 per cent by 2050. This can be realised by replacing the still common paper-based communication and planning by highly connected IT solutions, by efficient cooperation among European railways and industry bodies, and finally by Big Data applications, deep learning and predictive maintenance to make better use of the available resources.

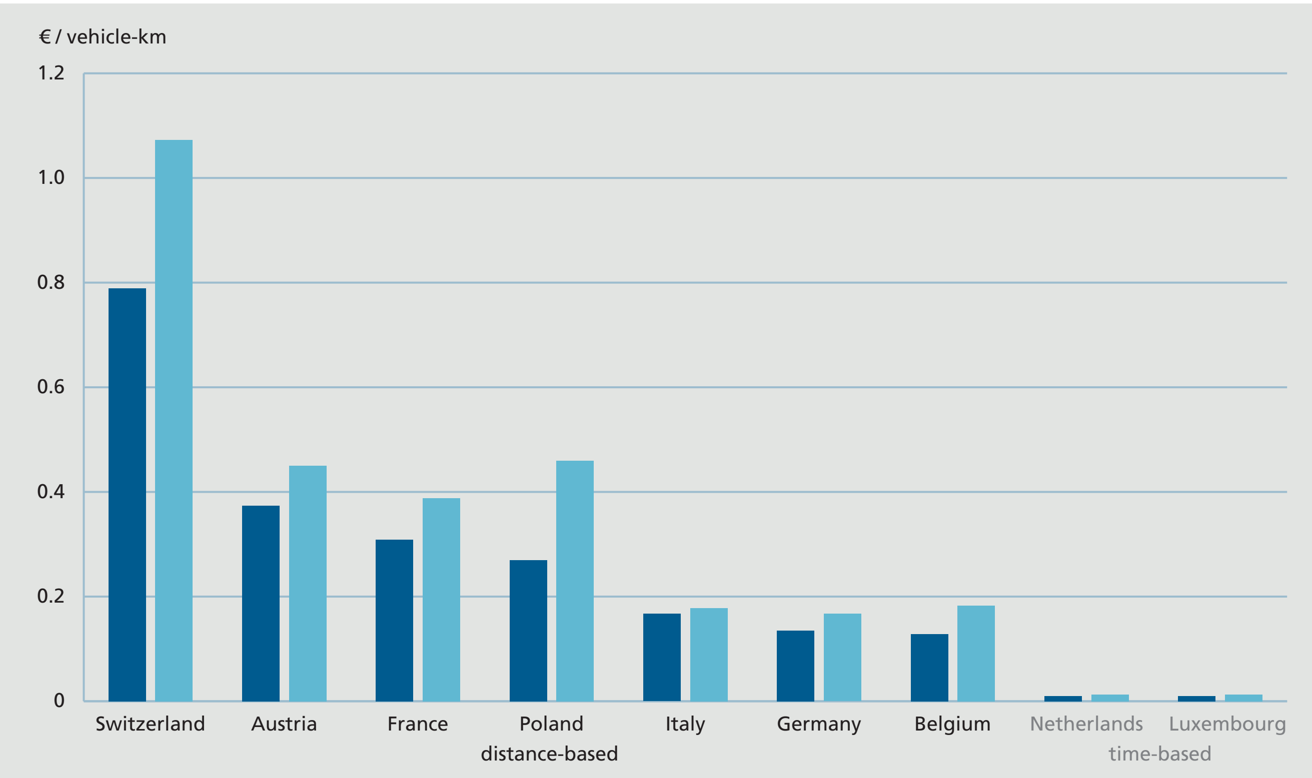
FIGURE 5: National track access charges for average freight trains



Rest of Europe *LowCarb-RFC corridors* **value taken from Lopes (2014).*

Source*: Fraunhofer ISI with data from EC (2016) and Lopes (2014)*

FIGURE 6: Tariff structures for HGVs on motorways in selected countries



HGV 40t, Euro-6 *HGV 40t, Euro-3*

Source*: T&E (2016)*

Table 2 summarises the developments of generalised costs in 2050 relative to 2015 together with keywords from the relevant scenario assumptions for rail and road. In contrast to the moderate and similar cost developments of road and rail in the BAU scenario, the two modes develop in completely different directions in the Pro Rail scenario. A cost decrease for the railways by two thirds is contrasted with a cost increase for trucking of 25 per cent. This corresponds to a 367 per cent relative price difference for trucking compared to rail freight.

TABLE 2: Assumptions and cost reduction potentials in the Pro Rail scenario

Cost category	Railways	Road haulage
Load factors	Up to 1500m trains; equal speeds; ETCS level 3; European wagon and cargo management **+209 %**	As BAU: Without longer trucks, only slight improvement possible in loaded hauls and use of truckload space **+10 %**
Infrastructure	Halving of track access charges by 2030 and marginal cost pricing by 2050 **–75 %**	Full cost pricing including surcharges on HGV motorway user tariffs for rail projects **+200 %**
Rolling stock	Strong decline in licencing and operating costs for locomotives, modular wagon systems, longer trains and European wagon management **–60 %**	Stricter environmental and safety requirements (capital costs +50 %); multiple fuels and more complex engines; higher environmental taxes and charges **+52 %**
Energy costs	Engine control. Driver assistance systems and aerodynamics **–35 %**	Same assumption as in BAU **–26 %**
Labour costs	Automation and standardisation, but also more labour-intensive customer demand; strong unions **–68 %**	Wide restriction of automation; strict enforcement enforcement wage levels and of social legislation **+10 %**
Administrative costs	Common use of highly efficient IT solutions for management, horizontal cooperation, Big Data and deep learning **–70 %**	Same assumption as in BAU **–20 %**
Total generalised costs	Extremely deep cuts across all cost categories; main driver is train utilisation and wagonloads **–66 %**	Main drivers for increasing costs are infrastructure charges and rolling stock regulations **+25 %**

Source: Fraunhofer ISI

3.3 IMPLEMENTING THE PRO RAIL SCENARIO

Modal shift decisions in freight transport are usually made once certain thresholds of cost differences are exceeded. This is certainly the case with a change in relative prices above 300 per cent. It can therefore be expected that, under the assumptions taken in the Pro Rail scenario, massive amounts of freight are shifted from road to rail. The rail networks need to be prepared to accommodate these volumes. This can be done by large investments, by closing smaller gaps, by increasing the carrying capacity per train, by allowing more trains on the network or by optimising processes across all the actors involved in rail transport.

External and internal developments are key pre-conditions to these massive and unprecedented efficiency gains in the railway sector: strong and coordinated political commitment, rapid implementation of capacity extension programmes and consistent structural reforms in the direction of a lean management culture within the railway companies.

4 DECARBONISING ROAD TRANSPORT

4.1 STATUS QUO: TRENDS AND CHALLENGES

We need a six-fold increase in CO_2 productivity in order to achieve the EU emission reduction targets in the 2011 EU Transport White Paper. To set the scene, the following section briefly describes the major trends of demand development, the lack of lorry drivers, the capacity limits of digital and transport infrastructure, regulations and policies, and issues of public acceptance. On this basis, the following chapter then describes the drivers of a positive road haulage future.

German logistics experts are very optimistic about the development of transport volumes in Germany: 66 per cent believe that they will continue to increase in the coming years (Continental AG 2016). At the same time, however, the German Federal Office for Goods Transport predicts rather moderate growth of 0.2–1.4 per cent until 2021 (DVV Media Group GmbH 2018). Over the past few decades, three *major trends* have influenced the demand for transportation: logistics, the structure and the volume of goods.

Unattractive social and economic working conditions, a negative image and the fact that the German military no longer trains drivers have caused a *shortfall of* about 15,000 trained *truck drivers* in Germany (Automobilwoche 2012). For the road transport scenario developed in this working paper, the lack of truck drivers has important implications: the wages of skilled drivers will most likely rise as their bargaining position improves. This will generate pressure to introduce automated driving. Autonomous trucks and platooning may help to maintain road haulage productivity. The increasing lack of truck drivers might therefore increase the technology and productivity gap between road haulage and rail freight in favour of the former.

Both road and rail freight have to deal with major maintenance works and increasing passenger transport on their *infrastructure* networks. Capacity investments are restricted by financial, physical and political (acceptance) limits. The conditions of the German road infrastructure are already causing inconvenience to road freight transport, and further weight restrictions or complete bridge closings, for instance, may become necessary in the near future.

The *image of road transportation* has suffered from the fact that it is the only large key source category in which greenhouse gas emissions increased between 1990 and 2016 in the EU-28. Furthermore, truck drivers attempting to overtake others travelling at roughly the same speed, accidents, noise and pollution have contributed to the negative image of road haulage for years. However, automated lorries are also likely to face resistance from the industry, drivers and the general public (Slowik and Sharpe 2018). Nevertheless, continuing noise reduction, increasing vehicle efficiency and truck safety due to driver-assistance systems and automation as well as low-emission trucks have the potential to improve the image of road haulage.

National and supranational *regulations and policies* such as pricing policies, road pricing, energy tax rates and bans of at least certain diesel cars have addressed market failures and will continue to do so. These measures are already moving the tipping point forward at which alternative engines become economic for light-duty vehicles.

4.2 DRIVERS OF A POSITIVE ROAD HAULAGE FUTURE

Road freight transport has inherent conveniences such as door-to-door delivery and the absence of technological and organisational barriers. Furthermore, technological developments are successively reducing its inherent inconveniences such as safety issues, lower energy efficiency and the possibility of efficiently bundling large volumes of freight. It is often easier for road haulage to adopt information and telecommunication innovations because its innovation cycles are much shorter than rail's due to much larger batch sizes. Finally, certain economic developments contribute to shifting demand from rail to road transport (see section 2.1).

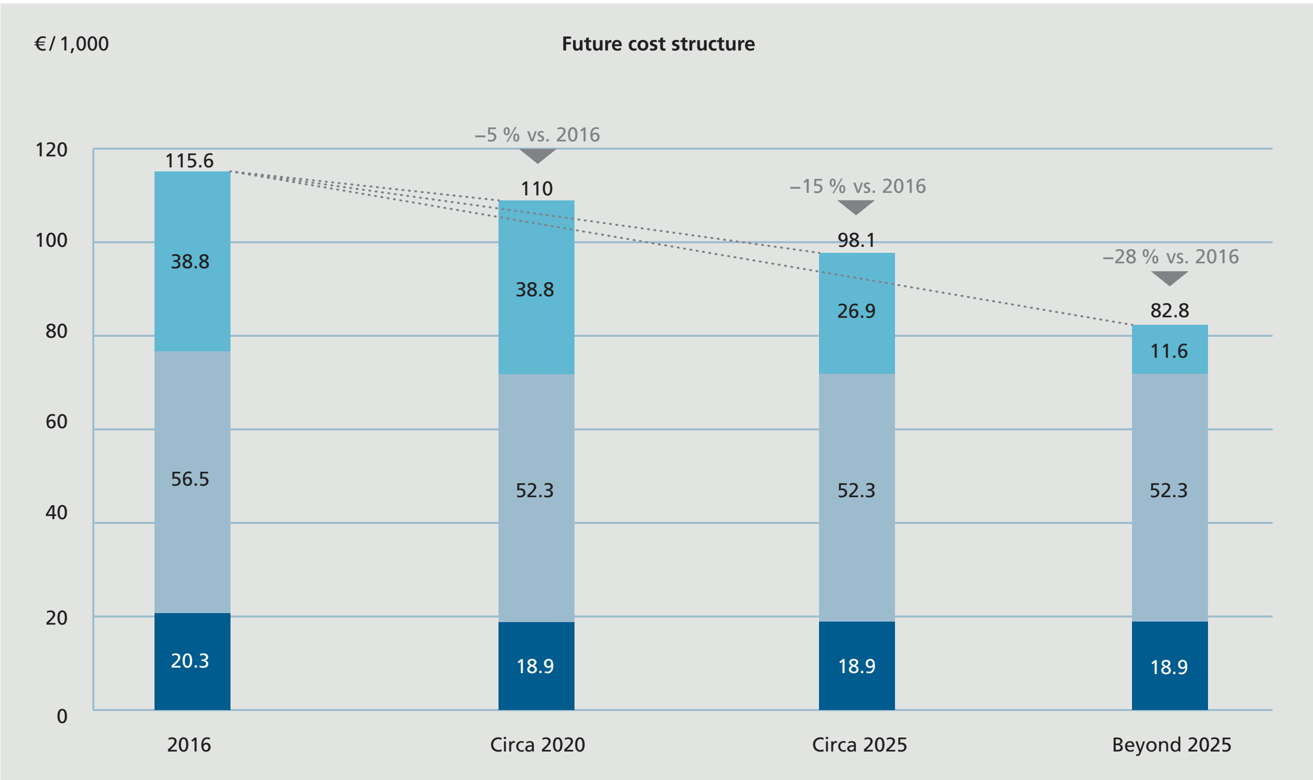
Vehicle efficiency is considered the biggest lever to reduce road freight's energy demand (OECD and IEA 2017). This is defined as the economically realisable potential of engine optimisation, idling reduction and lightweight materials as well as improvements in engines, drivetrains and transmissions. Further potential exists in aerodynamics, low rolling resistance tyres and tyre pressure systems and hybridisation.

Besides vehicle efficiency, *logistics and extra-long trucks* offer a wide array of potential efficiency improvement measures. The most significant ones are: extra-long trucks with a length of 17.80 to 25.25 m, improved vehicle utilisation, the Internet of things and blockchain technology, and integrated platforms.

Digitalisation, driver-assistance systems and automation also offer further potentials for efficiency improvement: Improved traffic information as well as connected and autonomous driving will contribute to the safety and efficiency of road transport. Connected supply chains are being fostered by the implementation of mobile networks along high-speed rail networks as well as motorways. Connected trucks communicate with their surroundings or the repair shop via vehicle-to-infrastructure or vehicle-to-vehicle technologies as well as remote diagnostics. Driver-assistance systems can include feedback devices that monitor and reward more fuel-efficient driving. SAE Level 3 (conditional automation) features such as platooning, real-time communication between trucks via V2V/dedicated short-range communication (DSRC) and motorway pilots capable of limited self-driving are mostly legal questions, which should be resolved by 2020. Platooning via electronic coupling should compensate the lack of truck drivers and enable fuel savings between 5 per cent (20m gap) and 15 per cent (4m gap) for a three-truck platoon travelling at 80 km/h (OECD and IEA 2017). Remotely-driven and autonomous lorries could penetrate the vehicle market before autonomous cars do, because driver training, benefits and salaries constitute 30 to 60 per cent of the carrier costs of road haulage (OECD and IEA 2017). Furthermore, motorways constitute a relatively predictable and stable driving environment and the technical viability of such trucks was demonstrated by the US-based self-driving truck company Otto in 2016.

As the Figure 7 illustrates, pwc authors expect autonomous driving technologies to influence the structure in several steps. In the years from 2016 to 2020, the costs of drivers are expected to remain stable, while variable and fixed costs are already expected to drop from 56.5 to 52.3 per cent and 20.3 to 18.9 per cent, respectively. Beyond 2025, fixed costs are expected to remain relatively stable but driver costs are then expected to drop from 38.8 per cent in 2020 to 26.9 per cent in 2025 and to only 11.6 per cent in the longer term.

FIGURE 7: Future cost structure of trucks equipped with autonomous driving technologies



Fixed ***Variable*** ***Driver***

Source: *pwc 2016*

We integrated these assumptions into our scenarios to the extent that rolling stock costs are modelled to increase to 110 per cent of 2015 levels by 2030, and then decrease to 105 per cent (see chapter 4.4). However, major issues of vehicle and software certification, liability, security and privacy need to be addressed and resolved beforehand. Obviously, rebound effects may offset any energy-saving benefits on the system level (OECD and IEA 2017).

There are numerous *drivetrain options* to increase efficiency, reduce or eliminate local pollution and decarbonise trucks. These options differ by truck category. Prospects are relatively clear for small trucks with gross vehicle weights (GVW) below 3.5 t (light-duty vehicles, LDV) and trucks up to 7.5 t but are still unclear for long-distance trucks with GVWs above 16 tons. For long-distance transport and heavier trucks, the following propulsion options are being discussed in the literature (OECD and IEA 2017; Wietschel, Schade and Mader 2017):

- Trucks operating on electrified roads, either with a catenary (overhead power line) i.e. trolley trucks or trolley-hybrid trucks, or with a ground-level power supply.

- Hydrogen fuel cell trucks also seem a feasible option for long-distance road haulage given that fuel cells are now being tested in regional trains that are even heavier than trucks. Of course, technically, it is still unclear how to install the fuel cell system including the tanks in the vehicle.

- Trucks operating with a combustion engine and liquefied natural gas (LNG). To achieve full decarbonisation, the LNG will need to be produced either from biomass (biogas) or from renewable electricity (power-to-gas, PtG).

- For heavy trucks, batteries are currently only considered an option for short to medium range distances and as supplementary propulsion for long-distance trucks operating on electrified roads.

For any use of lorries, there exists at least one zero exhaust emission option that could become reality until 2050 using reasonable assumptions. Therefore, the shares of electrically propelled transport performance on the corridors are assumed as follows.

TABLE 3: Assumed electrically propelled transport capacities on the RALP Corridor

Scenario	2030	2050
Pro Road = Full employment of dynamic charging infrastructure	50 %	80 %
Business-as-Usual: further demonstration projects for dynamic carging	3 %	8 %
Pro Rail: no investment in dynamic charging	0 %	8 %

***Source**: Fraunhofer ISI*

Since transport flows are less bundled on the North Sea-Baltic Corridor (Benelux—Poland), infrastructure deployment is assumed to be slower here. In conclusion, the race for sustainable road haulage in a Pro Road vision will take place between road-powered, battery and hydrogen fuel cell trucks.

4.3 SCENARIO NARRATIVES: THE PRO ROAD VISION

The basic narrative of a Pro Road vision builds on the arguments that road haulage can become at least as clean as rail (zero exhaust emissions), fully decarbonised (zero CO_2), reliable (little congestion) and safe (zero accidents). Furthermore, adverse impacts like the lack of drivers can be remedied and road haulage can further reduce its costs (larger vehicles and digitalisation) and increase its efficiency (also by digitalisation and cooperation). In such a world, road freight would clearly triumph over rail freight, simply because many of the arguments favouring rail (safety and certain environmental aspects) disappear, while arguments in favour of road (like costs and flexibility) are augmented or at least maintained.

Two major drivers of such a Pro Road vision can be identified: (1) *digitalisation* in a broad sense enabling autonomous driving, accident avoidance, route and traffic management as well as cooperative logistics improving the efficiency and costs of road haulage, and (2) *alternative propulsion(s)* enabling zero emissions and full decarbonisation of road haulage.

Apart from technical solutions, the *lack of truck drivers* could also be remedied through rising immigration, occupational reorientation and a positive development of social and employment conditions due to the European Directive on the posting of workers (see Chapter 4.4). Finally, technological developments will contribute to making driving itself less stressful and will eventually enable remotely controlled and automated trucks.

Concerning *infrastructure capacity limits*, the development of rail freight is heavily dependent on the development of some overstressed sections of the rail network and on upgrading and constructing new combined traffic terminals. However, local resistance is hindering development of overstressed sections, some terminals cannot be enlarged, and the new combined traffic terminals must be built at strategic locations that can be difficult to acquire. These facts are very likely to contribute to a lower growth of combined transport than predicted in the official traffic forecast for 2030. The volumes not absorbed by combined transport will contribute to the growth and payload efficiency of road haulage. Furthermore, improved construction site management and the development of a traffic analysis system contribute to relieving road congestion in the future. Additional comfortable parking lots along motorways improve the quality and safety for truck drivers. Autonomous and remotely controlled trucks can use the free capacity on motorways at night, helping to mitigate road capacity limits as well. However, the road system's charging and distribution network are considered the major barrier to the introduction of alternative propulsions (Furtado 2018).

The publication of the European *vehicle efficiency regulations* expected in 2018 will help road haulage companies choose the most efficient vehicles for their purposes, optimise their cost calculations and reduce their costs.

Concerning the financing of the German motorway infrastructure, the introduction of *road pricing* for cars is not unlikely and this would generate the finances for even more investments in roads. Furthermore, a smart tolling solution enabling traffic management as promoted by the 'Europe on the Move' initiative could contribute to reducing congestion. It is expected that road pricing for trucks and eventually for cars will incentivise the use of alternative fuels, helping to achieve the zero pollution and zero GHG objectives.

Differentiated vehicle taxation on vehicle purchase and operation, including fuel taxes, is expected to foster stricter fuel economy standards and incentivise the purchase and operation of *efficient trucks*. The combined potential of reducing idling through start-stop systems, lightweighting, optimised transmissions, aerodynamic fittings, low rolling resistance tyres and hybridisation could be as high as 2.5 per cent per year between 2015 and 2035 (OECD and IEA 2017).

Extra-long trucks could contribute to greater efficiency. In particular, expectations are high that the 14.90 m semitrailer, which is not entirely compatible with existing pocket wagons for combined traffic, will contribute to a significant modal shift from rail to road.

Internal and external *logistics* optimisation will drive improved vehicle utilisation and bundling of cargo flows through the introduction of fleet management software and standardised transport data platforms, carrier alliances and freight marketplaces. The Internet of things and blockchain technology will also contribute to more efficient and secure collaboration among players.

The advancement of digital technologies and their application across supply chains and fleet management, collaboration among shippers and the optimisation of vehicle operations are expected to lead to *systemic improvements* in road freight and logistics. SAE Level 2 features such as emergency braking systems, adaptive cruise control, lane keeping assist systems as well as driver-assisted truck platooning are already being adopted in the truck fleets at costs of about 1,800 USD per truck. More advanced *driver-assistance systems* will be pushed by ever increasing regulatory safety requirements.

Platoon service providers may emerge to seize the limited commercial benefits that this technology holds. They will use business models with different levels of complexity from scheduled platoons through on-the-fly to orchestrated platooning (Bernhart and Roland Berger 2016). Platooning is expected to become reality between 2025 and 2035 (Randelhoff 2017). The trend of platooning might consolidate or at least integrate the highly fragmented road haulage market, potentially contributing to higher loading factors. The potential of lower labour costs, higher productivity due to obsolete driving time restrictions and higher fuel efficiency is estimated to lead to 20 per cent lower operating costs (ITF and OECD 2017).

The lack of skilled truck drivers may well push the introduction of *highly automated trucks* (SAE level 4) that can be remote controlled, making truck driving a much more attractive profession. In turn, this could influence the development of truckers' wages, hindering the amortisation and therefore the introduction of fully autonomous trucks. Uber started transporting cargo using "self-driving" trucks monitored by a driver on a highway in Arizona in March 2018 (Wakabayashi 2018).

Fully autonomous trucks could reduce labour costs by up to 90 per cent (Randelhoff 2017), endangering more than half of road haulage jobs (ITF and OECD 2017). This would contribute significantly to reducing operating costs by 10 per cent to

35 per cent (McKinsey 2016). Disruptive scenarios expect the introduction of fully automated trucks (SAE Level 5) as early as 2021; conservative estimates by 2030 (ITF and OECD 2017).

The deployment of *alternative fuels* with low well-to-wheel emissions will help to address multiple energy policy goals. The IEA considers a 60 per cent reduction in European road freight energy demand possible by 2050 (OECD and IEA 2017).

However, the potential measures have diverse *impacts* on energy supply diversification, climate change and air pollution. The effects of potentially lower transportation prices can also include the decentralisation and specialisation of production sites. The resulting higher transport intensity could result in constant or only slightly lower end prices and a growing demand, e.g. for first and last mile transport (Randelhoff 2017). And the investment costs could lead to more leasing and fleet management models by OEMs and specialised suppliers.

4.4 COST AND PERFORMANCE ASSUMPTIONS FOR ROAD HAULAGE TO 2050

This chapter presents a brief overview of the distribution of cost shares in Germany and then describes the cost assumptions underlying the Pro Road scenario.

In 2013, the *cost shares* for long distances in Germany were as follows (BGL 2017): Kilometre-dependent operation represented 48.28 per cent of total costs, followed by personnel (28.61 per cent), (fixed) vehicle commissioning (10.77 per cent), administration (9.31 per cent) and driver expenses (3.03 per cent). These shares vary for shorter distances in the following ways: the shorter the distance, the higher the share of personnel costs (up to almost 44 per cent), whereas operation drops to slightly below 28 per cent and administration rises to almost 15 per cent. Vehicle commissioning remains at about 12 per cent and driver expenses drop to about 1.5 per cent. The scenarios' *expected characteristics* required assumptions on the development of load factors as well as on the costs for infrastructure, rolling stock, energy, personnel and administration. The following paragraphs explain the road haulage assumptions made when modelling the Pro Road scenario compared to 2015. The assumptions for the other transport modes in the Pro Road scenario are identical to the BAU assumptions in the Pro Rail scenario description.

Road haulage *load factors* are expected to increase slightly in all scenarios. In the Pro Road scenario however, mostly road-bound hub-and-spoke networks, backhauling, integrated supply chains, automated freight matching and larger trucks are expected to improve vehicle utilisation more than in the other scenarios. Therefore, the load factor in this scenario increases to 115 per cent by 2030 instead of to 105 per cent as in the other scenarios, and to 125 per cent by 2050 instead of to 110 per cent.

Infrastructure costs in road haulage are expected to decrease to 80 per cent by 2030 and to 60 per cent by 2050 compared to remaining stable in the BAU scenario and increasing by 50 per cent by 2030 and by 200 per cent by 2050 in the Pro Rail scenario. The decrease is because road tolls in Germany are lower for cleaner trucks, which are therefore expected to diffuse quickly into the fleets. Furthermore, dynamic road tolling and automatic driving could contribute to more vehicles driving at lower fares during the night. Extending the motorway network will distribute the cost burden of the necessary investments across more "shoulders". Charging may be adapted so that larger and potentially also heavier trucks may be more economical per load-unit. Larger and increased numbers of vehicles on more tolled roads mean lower tolling rates per ton-kilometre.

The *rolling stock* costs for road haulage are expected to increase to 110 per cent by 2030 instead of 104 per cent as in the BAU and 115 per cent as in the Pro Rail scenario. This is due to the (partially forced) proliferation of new and expensive digital equipment, aerodynamic improvements and electric drivetrains. However, remote diagnostics soon start to slow down this cost increase. Between 2030 and 2050, these investments will pay off for the sector due to economies of scale and the long lifetime of electric drivetrains, and these costs will drop back down to 105 per cent of the 2015 cost level. In contrast, these costs are expected to increase to 109 per cent in the BAU and to 125 per cent in the Pro Rail scenario.

Energy costs for road haulage are expected to increase significantly by 32 per cent at first and then return to 2015 levels in the BAU and Pro Rail scenarios (in which they remain a little higher throughout 2050). In the Pro Road scenario, in contrast, they are expected to drop to 90 per cent by 2030 and to 74 per cent by 2050. 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.

Personnel costs for road haulage are expected to decrease to 70 per cent by 2030 and to 30 per cent by 2050 in the Pro Road scenario (other studies[1] expect reductions of up to 90 per cent) compared to dropping to 90 per cent and then to 80per cent in the BAU scenario and rising to 105 per cent and then to

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

110 per cent in the Pro Rail scenario. This drop is the result of longer vehicles, automation and remote control decreasing the need for staff and making the jobs that do remain more attractive.

Administration costs for road haulage are expected to drop in all scenarios, but the decrease is stronger in the Pro Road scenario: to 85 per cent instead of 95 per cent (other scenarios) by 2030 and to 60 per cent instead of 80 per cent (other scenarios) by 2050. This is due to the expected rapid development of digital administration tools and lower insurance rates due to safer vehicles.

4.5 CONCLUSIONS

As long as energy prices remain low for whatever propulsion trucks use, the development of demand is not likely to change significantly in the next years and decades. Logistics will continue to introduce new tools to meet the demand of the transportation market for high frequency delivery, a sector in which rail cannot play a major role. The structure of goods is also expected to continue to develop away from traditional rail formats. If any unexpected changes occur, road haulage can respond more quickly to new opportunities than rail can. Safer, quieter and less polluting trucks driving in platoons instead of trying to overtake each other at very low speed differences help to increase public acceptance of them in the coming years. Improved traffic information, platooning, driver-assistance systems, mobile networks as well as connected, remotely-driven and autonomous lorries will drive down the operating costs and increase the energy efficiency of road haulage. Thus, without substantial policy intervention to improve the rail system and promote the use of rail freight, it is much more likely that the Pro Road vision will become reality than the Pro Rail vision.

Table 4 summarises the main assumptions and the average cost evolutions from 2015 to 2050 for rail and road transport in the Pro Road scenario. Interestingly, the use of new technologies like digitalisation and automation let drop costs in both cases, Pro Road and Pro Rail, against 2015. Main drivers of the stronger drop of road costs are more efficient use of road infrastructure due to demand shifts to road, the low costs of electric propulsion and the replacement of human drivers by automation.

TABLE 4: Assumptions and cost reduction potentials in the Pro Road scenario

Cost category	Railways	Road haulage
Load factors	As BAU: 740m trains; European wagon management and cargo trading platforms **+45 %**	Longer and heavier trucks, European cargo trading platforms, horizontal cooperation and mergers **+15 %**
Infrastructure	As BAU: Policy plans: halving rail track access charges **–25 %**	No more environmental charges; more traffic sharing fixed infrastructure costs; heavier trucks decreasing costs per ton **–40 %**
Rolling stock	As BAU: soft removal/extension of regulatory barriers; management of wagon fleet **–20 %**	New digital equipment, aerodynamic elements and electric drive trains by 2030; payoff of these costs towards 2050 **+5 %**
Energy costs	As BAU: Full electrification and improved energy efficiency through driver assistance (–5 per cent) **–12 %**	Growing prices plus multiple effect of efficiency gains, regulations, alternative energy sources, driver assistance systems and automation **–26 %**
Labour costs	More or less stable for drivers; decrease for local workers due to automation of terminals and track works **–20 %**	Longer vehicles, automation and remote control of trucks **–70 %**
Administrative costs	Productivity increases mainly in administrative structures (+25per cent); some extra management costs **–25 %**	Rapid development of digital administration tools and lower insurance rates due to safer vehicles **–40 %**
Total generalised costs	Dominant drivers: rolling stock and energy costs **–25 %**	Main drivers: more efficient infrastructure use, energy efficiency and the replacement of human labour **–35 %**

Source: Fraunhofer ISI

5 MODELLING TRANSPORT IMPACTS

5.1 INTRODUCTION

This section describes the approach and the results of the transport impact assessment study carried out within the Low-Carb-RFC project. Working Paper 7 (van Hassel et al. 2018) provides a detailed report. The main purpose of the transport impact assessment is to provide a method and a set of indicators to assess alternative scenarios against a baseline scenario (business as usual) to study the modal shift potential and its contribution to climate change mitigation. The model is constructed for the main freight corridors crossing Germany and, in particular, the German federal state of North Rhine-Westphalia (NRW). The two main rail freight corridors considered in this project are the European Commission's:

- RFC no 1: Rhine-Alpine (RALP) from Antwerp / Rotterdam via Duisburg and Basle to Genova and the southern branch of the RFC.

- RFC no. 8: North Sea-Baltic (NSB) from the Dutch / Belgian seaports to Poland and the Baltic states. This study only considers the western part of this corridor to Poland.

The method should allow the assessment of different scenarios in which conventional rail improvement and policy packages are considered, including emerging industry and technology trends as well as completely new transport solutions. The project develops two scenarios: a Pro Road and a Pro Rail scenario. As both scenarios go to extremes with regard to cost cuts and quality improvements, a Modest Road (Mod Road) and Modest Rail (Mod Rail) scenario are added.

These different scenarios affect cost elements of either road or rail transport. In addition, the parameters in a future scenario include changes in infrastructure (shorter distances when a new railway line is used), different speeds and reliability levels. All have an effect on the generalised costs and therefore the choice of transport mode. This influences the total ton-kilometres (tkm) and vehicle-kilometres driven in NRW.

The main objectives of this paper are to:

- Develop a method to assess different scenarios (BAU, Mod Rail, Pro Rail, Mod Road and Pro Road) for the years 2030 and 2050.

- For the different scenarios and both freight corridors, determine the change in modal shift, transport volume and capacity needs and the effects on the infrastructure in NRW.

- Determine the total greenhouse gas emissions per year for each scenario.

5.2 LITERATURE REVIEW

The first main research activity was a literature review of freight models and their applications. This revealed there has already been a lot of research on various types of freight model. Each model has its own specific application and purpose, but a main trend is to locate the decision-making process at company level. This implies the need to model the total cost of logistics (including shipment size, inventory cost and safety stock). The project focuses on the two main freight corridors crossing NRW (Rhine-Alpine and the North Sea-Baltic). For these corridors, ports can form the starting point (or end point) of a transport chain. However, inter-corridor flows (without a direct link to a seaport) are also possible. Therefore, cargo flows originating from the ports (maritime flows) and continental flows need to be taken into account. The freight transport modes considered are:

- Road
- Intermodal rail
- Intermodal inland waterway transport (IWT, especially important for the ports of Antwerp and Rotterdam)

In the methodology applied, the most important attributes are:

- Out of pocket cost, i.e. the immediately visible costs, and
- time for the entire trip from door to door

- Both for road, intermodal rail and intermodal IWT shipments.

Data from the ASTRA model can be used. The ASTRA (ASsessment of TRAnsport Strategies) model is a system dynamics model on a European scale that has been further developed since 1997 by three partners (Fraunhofer-ISI, IWW Karlsruhe and TRT Trasporti e Territorio). It is used for the strategic assessment of policy scenarios and considers feedback loops between the transport system and the economic system. The ASTRA model consists of eight interlinked modules. For a detailed description of the ASTRA structure, see Schade (2005) and Fiorello et al. (2010).

5.3 METHOD

The method used in this working paper is designed to assess the impacts of different future scenarios on the modal choice and GHG emissions for two main freight corridors through NRW. The two corridors (RALP and NSB) in this project are mapped in Figure 8. For each corridor, we distinguish seven different cargo flows (the directions in brackets concern the NSB corridor):

- Transit from North (West) to South (East) (from blue to green)
- Transit from South (East) to North (West) (from green to blue)
- From NRW to South (East) (from grey to green)
- From NRW to North (West) (from grey to blue)
- From South (East) to NRW (from green to grey)
- From North (West) to NRW (from green to blue)
- Internal NRW flows

The main indicators determined for each of these different cargo flows are:

- Ton-kilometres (Road, Rail, IWT)
- Twenty-foot equivalent unit-kilometres—TEU-km (Road, Rail, IWT)
- (Loaded) vehicle kilometres (Road, Rail, IWT)
- Modal split (TEU or ton)

In order to calculate the modal split[2], we determine the generalised costs for each mode of transport. The main purpose of having four different cargo flows is that each of these cargo flows features different cost structures. IWT cargo flows for dry and liquid bulk are usually unimodal (without pre and post haulage), while there is much more inter- or multimodal transport[3] for containers and general cargo. This can be seen in Table 5.

With respect to intermodal and multi-modal transport, we distinguish two alternatives:

- Maritime flows (a seaport as origin or destination)
- Continental flows

For the maritime flows, the origin (or destination) of the cargo flow is a seaport. This means that there is only post- (or pre-) haulage and a handling cost.

In order to determine the modal split for each mode of transport (or transport option), the generalised transport costs are calculated. Besides the cost functions, the distances are also needed as an input to:

- Calculate the generalised cost
- Calculate the ton-kilometres and vehicle-kilometres involved

The cost functions for road, rail and IWT are taken from van Hassel et al. (2016) and adapted to incorporate cost changes due to possible future developments. These cost functions are described in detail in the full working paper (Van Hassel et al. 2018).

5.4 DATA

As stated above, the model needs different types of data: cargo data, distance data and cost data of the different transport options. With respect to the cargo flow data, we distinguish different main cargo groups:

- Containers (unitised)
- Bulk cargo
  - Dry bulk
  - Liquid bulk
- General cargo

The data are taken from the ASTRA model.

Different sources are used for distance data. We calculate road distances using Google maps. Distances are calculated from the centres of the NUTS-2 regions.

2 The share of a certain transport mode on a transport link (origin destination pair).

3 Intermodal transport refers to container transport, while multi-modal transport is usually associated with general cargo.

The road distance data are determined for the following cases:

- Both OD matrices (30x30 and 40x40)
- From each rail terminal to the centre of a NUTS-2 region (needed for the pre- and / or post-haulage calculation
- Road distance for each OD pair on NRW territory

For rail transport, distances are determined between different rail terminals (containers and bulk) for the following cases:

- Both OD Matrices (30x30 and 40x40)
- Rail distance for each OD pair on NRW territory

We use OpenStreetMap data for the rail distances (OpenStreetMap 2015).

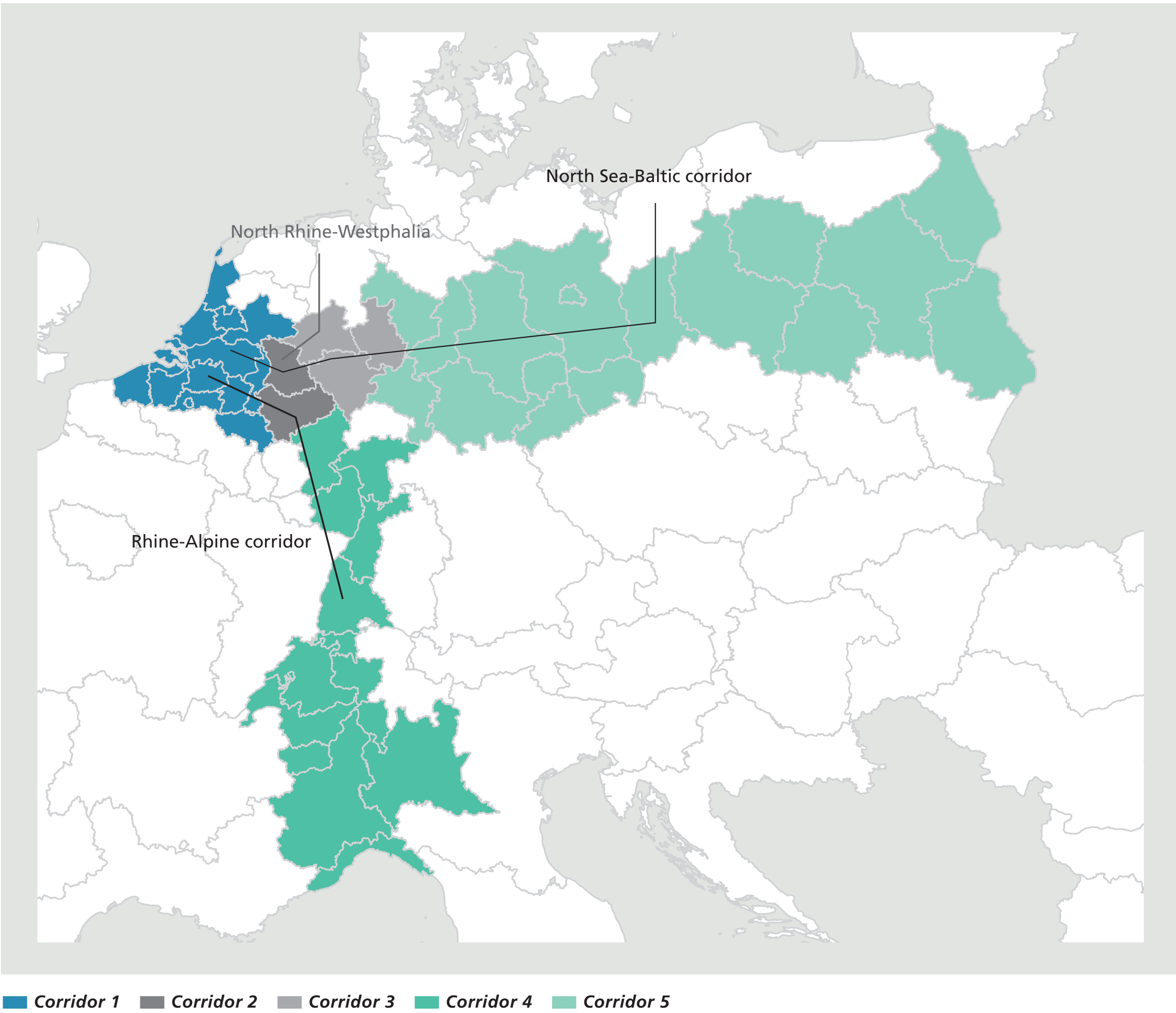
For IWT transport, distances are determined between different IWT terminals (containers and bulk, using Blue Road Map[4] (2017) for the following cases:

- Botch OD Matrices where IWT transport is possible (22x22 and 31x31)
- IWT distance for each OD pair on NRW territory

Different sources are used for the cost data. These data are collected for road, rail and inland waterway transport and taken from other research projects and data collected in the LowCarb project working group. See van Hassel et al. (2018) for a full overview of the data used.

4 http://www.blueroadmap.nl/.

FIGURE 8: Function of geographical zones in the transport impact analysis



***Source**: TRP / University of Antwerp and Fraunhofer ISI*

TABLE 5: Different forms of transport for the considered commodity types

	Unimodal			Inter- / multi-modal	
	Road	**Rail**	**IWT**	**Rail**	**IWT**
Containers	X			X	X
Dry bulk	X	X	X		
Liquid bulk	X	X	X		
General cargo	X			X	X

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

5.5 MAIN RESULTS OF THE STUDY

The transport chain model is calibrated with transport flows generated by the ASTRA-EC System Dynamics model. It is then possible to calculate the modal split and the TEU-kilometres, ton-kilometres and vehicle-kilometres in North Rhine-Westphalia by applying the calculated spreading factor (μ). It is also possible to change the input parameters related to the cost structure and determine the impact of these changes on the parameters mentioned above. We can further consider the effect of changing freight flows (forecasts for 2020 and 2030). The changes to the input parameters are taken from the different scenarios:

- Pro Road scenario (WP 5, Doll and Köhler 2018)
- Pro Rail scenario (WP 6, Mader and Schade 2018)

Comparing the BAU scenario to the Pro Rail and Pro Road scenarios reveals the following differences:

- There are significant differences in terms of modal split. These differences depend on the inputs from the various scenarios. A Pro Rail scenario leads to a high market share of rail transport, mostly at the expense of IWT and road transport to a smaller extent. The Pro Road scenario has the opposite effect as it increases road market shares on the expense of IWT and rail to a smaller degree.

- In the bulk good segment, rail market growth in the Pro Rail scenario is fed equally by road and IWT transport. Nevertheless, the strongest impact of the Pro Rail scenario is on the modal share of IWT.

- Road transport retains a high market share in absolute terms, especially in NRW. This is mainly due to the short distances involved for the majority of transport volumes (within NRW) so that road transport is very dominant.

- In both scenarios, there is a very large increase in the TEU-kilometres, ton-kilometres and vehicle-kilometres for NRW and for each corridor as a whole. This is due to the increase in demand for freight transport (1.7 per cent growth). The number of vehicle-kilometres is smallest in the Pro Rail scenario, but the capacity of the railway infrastructure needs to be taken into account as well. This scenario is only possible if the rail infrastructure can accommodate such a strong increase in train vehicle-kilometres.

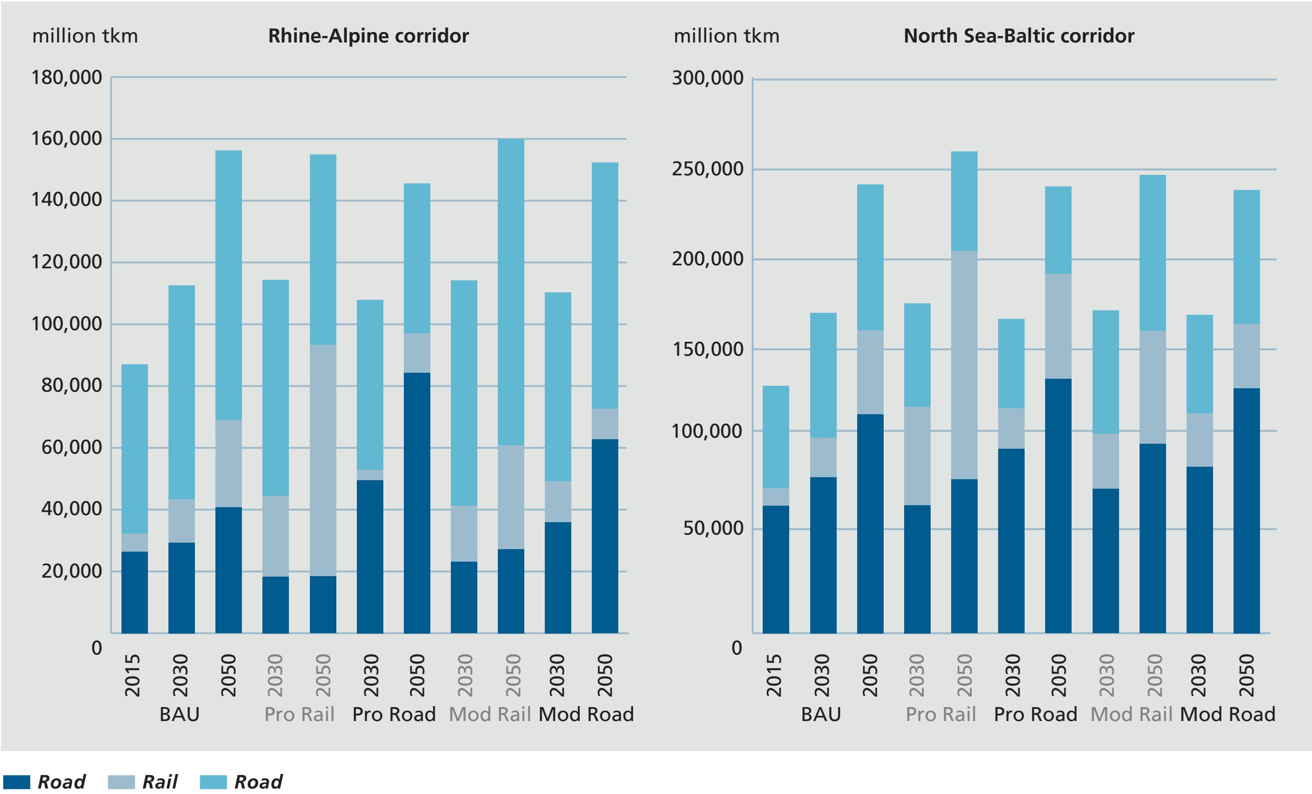
- With respect to CO_2 emissions, the absolute volume increases in all the scenarios. The smallest increases are observed for the Pro Rail scenario for both freight corridors (+ 35 per cent in 2015 for the RALP corridor and + 53 per cent for the NSB corridor).

Over the course of the LowCarb-RFC project, the results are interpreted as follows:

- The modal shift identified by the transport model constitutes a theoretical maximum of market reactions. In reality, we observe that modal shares are rigid and change only slowly over time. Limited network capacity and the inoperability of certain cargo types on rail are the most constraining factors. The model does not consider capacity constraints. However, the full-scale scenarios Pro Rail and Pro Road and their more moderate variants represent options for preparing the transport systems. Feeding back these results into the scenario assessments makes it possible to define respective investment strategies for these cases.

- Cost reduction scenarios need to be supported by policy and entrepreneurial strategies. The assumed cost reductions can only be realised if they are partly covered by the public sector and if the railways develop sufficient and partly radical innovations. Change management and institutional

FIGURE 9: Transport volumes on the corridors 2015 to 2050



***Source:** Fraunhofer ISI*

reforms are thus integral elements of the Pro Rail scenario, in particular. These issues are covered in detail by other reports of the LowCarb-RFC project.

- Concepts for inland waterway transport are crucial. The assessment of fixed rate GHG emission scenarios clearly shows that, even though unrealistically high market shares of the railways are computed, the reduction in GHG emissions due to modal shifts alone remains rather modest. Besides the fact that the fixed rate GHG emission concept deliberately excludes decarbonisation strategies of the railways and the power sector, the demand shift from IWT to rail is mainly responsible for this result. A low-carbon strategy that aims at curbing transport sector emissions needs to maintain a balance between all the climate-friendly modes.

- Real GHG mitigation potentials of modal shift scenarios need to consider other crucial factors. These include the decarbonisation of the power sector, the electrification of today's diesel-powered trains or the use of low-carbon combustion fuels, efficiency gains and developments in road and IWT transport. These issues will be assessed in a separate scenario evaluation process in the LowCarb-RFC study.

6 SUSTAINABILITY IMPACT ASSESSMENT

6.1 FUTURE DEVELOPMENTS THAT WILL CHANGE EMISSIONS

Any assessment of long-term transport impacts is related to a number of uncertainties that can only be overcome by making assumptions about future developments. At present, a large number of new technologies are cropping up, but it is not certain that all of them will succeed in a future market environment. The following technologies are of major importance to the impact assessment:

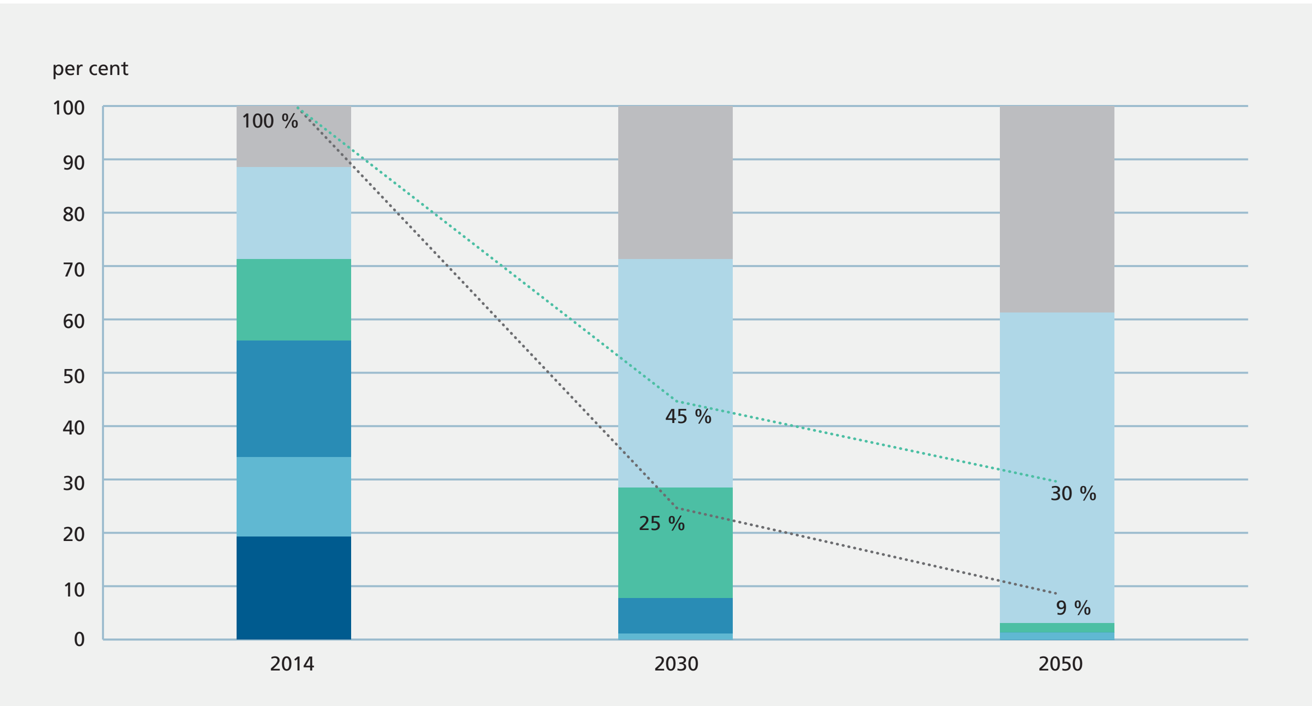
- Electric vehicles in road and rail freight transport
- Growth of renewable energies for electricity generation
- Proliferation of information technologies in transport

Electrifying Transport

According to EU requirements, all railway lines in all scenarios and on all corridor branches will be fully electrified by 2050, although the progress made towards this situation is assumed to vary in speed. The Rhine-Alpine Corridor will be fully electrified by 2030, whereas only 89 per cent of the North Sea-Baltic route will be electrified by then.

In road haulage, electrification enters the transport sector by overhead wires, battery electric and hybrid trolley 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 NSB route.

FIGURE 10: Energy production according to BMUB Klimaschutzszenario KS95



Nuclear *Lignite* *Hard Coal* *Natural Gas* *Wind* *Photovoltaics*

***Source**: Fraunhofer ISI*

Decarbonising power generation

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 per cent (KS95) developed by the German Ministry for the Environment (BMUB 2015) that has the target to reduce greenhouse gas emissions by 95 per cent in 2050 relative to 2005. As depicted in Figure 10, renewable energies will make up 97 per cent of the German energy production by then. The KS95 scenario was selected in order to show the additional impacts generated by a shift from road to rail and the implementation of new technologies (see above) in a climate-friendly environment.

Automation and ICT

The rapid 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. Additionally, autonomous driving and platooning technologies enable increased efficiency in road haulage and, to a lesser extent, in rail transport. Through full automation, we assume a 10 per cent efficiency gain in trucking in the Pro Road scenario, and 5 per cent for rail services in the Pro Rail scenario.

6.2 ASSESSING GREENHOUSE GAS EMISSIONS

Assessment principles

Climate impacts in transport constitute the leading sustainability indicator for the LowCarb-RFC study. Of all the challenges facing transportation, including safety, air quality and noise, climate change has the most profound and long-term impacts on ecosystems and human living conditions on a global scale.

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 conventional internal combustion engine (ICE) vehicles are derived from van Essen et al. (2011) for the year 2008. For reasons of simplicity, we assume these are still valid for the base year in the LowCarb-RFC study of 2015. Future developments are based on the findings developed in E3MLab / AUTH (2014) and depicted Figure 11. A strong increase in energy efficiency is observed in road transport, while railways are already relatively efficient in 2015.

GHG reduction potentials

The combination of the above-described measures, especially the switch 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 per cent in the RALP corridor and by 64 per cent in the NSB corridor, while the Pro Rail scenario only achieves a reduction of 41 per cent on the RALP and of 26 per cent on the NSB corridor. Both Mod-scenarios, i.e. the cases where cost reductions and electrification in all modes are considered 50 per cent the value in the Pro scenarios, have moderate impacts compared to BAU.

In 2050, ICE engines produce the largest share of GHG emissions and the large freight volumes transported by water are a major additional GHG emission source. However, there are no more diesel trains and all the motorways will be electrified in the Pro Road Scenario. The latter factor has a profound effect on the scenario's outcome, because no matter how much cargo trains and barges manage to transport, the bulk of goods will remain on the roads. Practically eliminating greenhouse gas emissions here, therefore, constitutes a huge step towards a climate-neutral freight transport sector.

As rail is already extensively electrified and only causes around 40 per cent of total transport emissions in the BAU, its further contribution is limited. If, however, it is assumed that only half the HGV traffic is powered electrically as in the Mod Road scenario, CO_2 emissions will more than double compared to the Pro Road case.

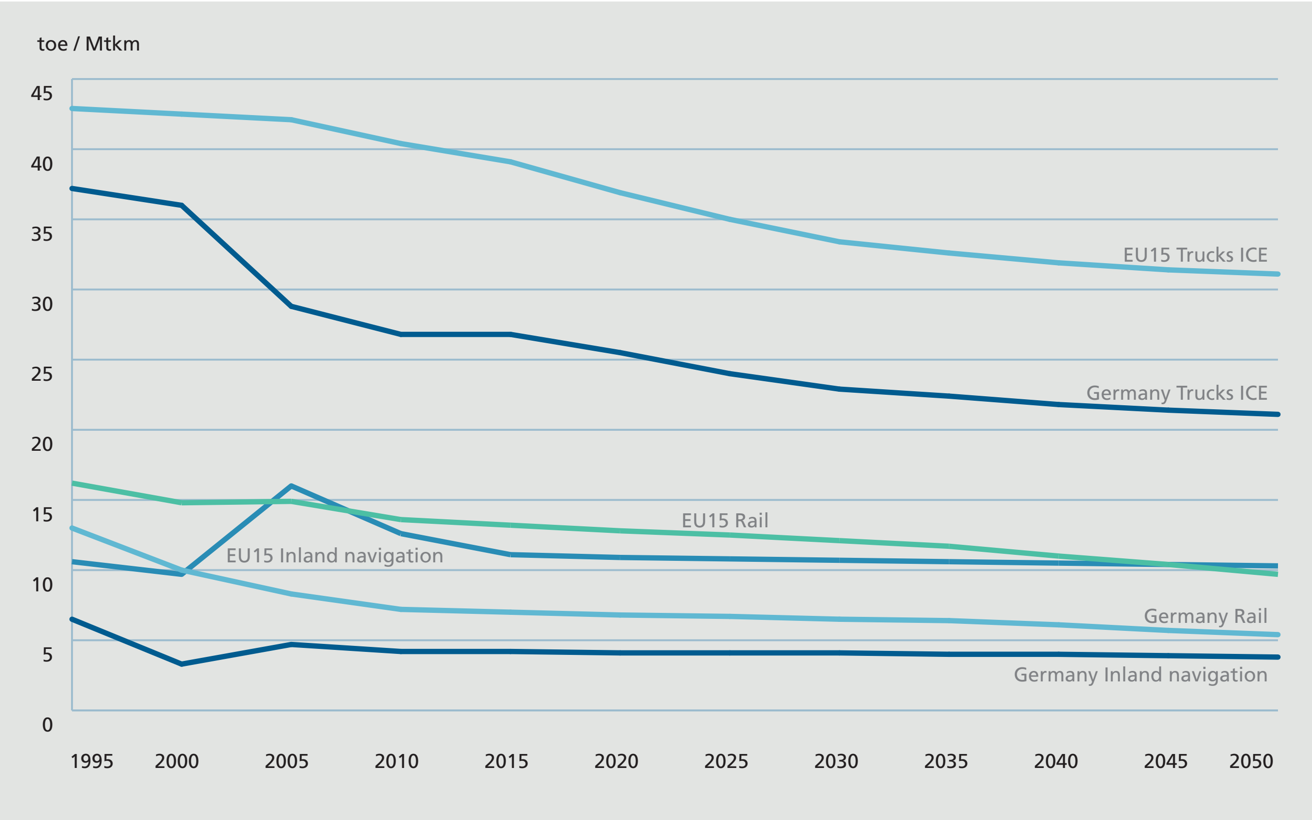
Electrifying all of road transport by 2050 is not impossible, but extremely ambitious. It therefore seems more likely that a scenario close to the Mod Road case will emerge than a situation close to the Pro Road case. From the narrow perspective of CO_2 emissions, we can conclude that road haulage decarbonisation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

6.3 EXTERNAL COSTS

The concept of external costs

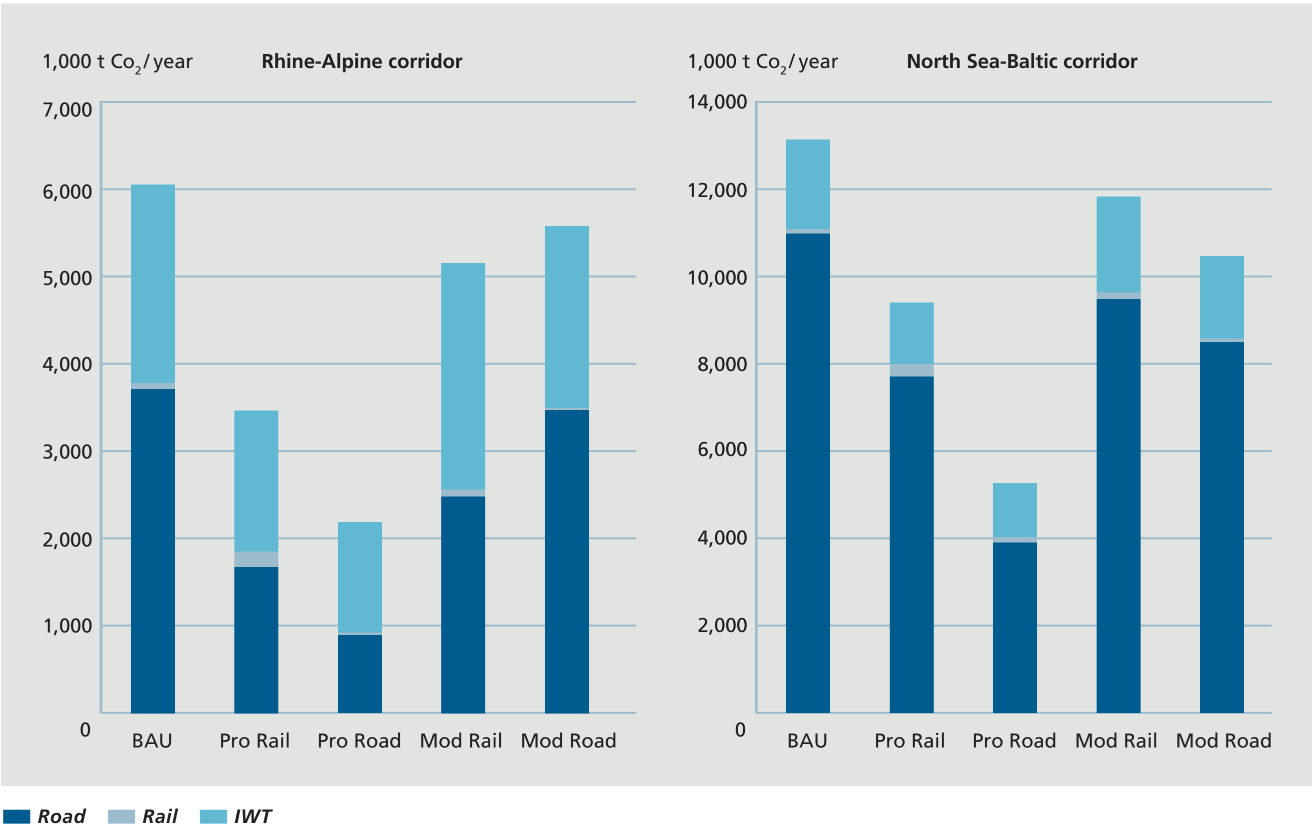
Besides its contribution to climate change, transport also has negative impacts on air quality, human health and the environment as well as causing noise pollution and accidents. These physical externalities, however, are difficult to compare in order to obtain a single value of sustainability compliance. Quantifying the impacts in monetary terms offers a more general indicator to quantify the sustainability impacts of certain human

FIGURE 11: Energy efficiency in transport



***Source**: PRIMES*

FIGURE 12: CO_2 emissions in 2050



***Source**: Fraunhofer ISI*

activities. This can be done by accounting for the actual damages caused (damage cost approach) or by estimating the cost of compensating for damages caused or for avoiding additional damages by reducing the environmental load below certain thresholds (avoidance cost approach). All three methods yield the "social costs", i.e. the financial implications of the impacts of transport on third parties and the environment.

The term "external costs" is frequently used. This denotes the social costs minus the payments made by the users, i.e. "internalised" social costs. This concept is relevant for pricing and taxation issues attempting to identify "missing" internalisation contributions. Our focus in this working paper is the damage caused by transport and we therefore prefer the simpler definition of social costs.

Climate Change

The external costs of climate change are derived for each scenario from the physical emissions by multiplying the greenhouse gas emissions by the specific social costs per ton of CO_2-equivalents. It is difficult to estimate CO_2 costs due to their global and long-term impacts on various aspects of human life and the ecosystem. It is possible to arrive at the monetary costs per emitted ton of CO_2-equivalents by estimating the potential damages or by estimating the avoidance efforts needed to remain below a certain atmospheric CO_2 concentration. In both cases, studies display wide ranges and a progressive slope of potential unit values over time. The latter is due to reaching tipping points in the global ecosystem and the progressively limited availability of cheap mitigation measures.

TABLE 6: Specific climate change costs

Unit cost estimates (€/t CO_2-eq)	Short-term	Mid-term	Long-term
	2015	**2030**	**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 (2012)*

Air pollution

The following sources were used to calculate pollutants: 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 (EC, 1997) is implemented for rail engines and thus the same improvements will take place as for ICE road vehicles.

Emissions from inland water vessels were assessed based on emission factors presented by UBA (2012) and future emissions in line with the BAU scenario for barges presented in Panteia (2013).

Nitrogen oxides (NOx) and particulate matter <2.5 µm (PM 2.5) serve as reference pollutants because these play the main role in current legislation on national and local emission ceilings. Emissions of particulate matter PM are determined by exhaust emissions and tyre and brake abrasion. The latter are considered to remain constant for road vehicles even if the vehicle is driven electrically.

Noise

The specific noise costs were derived from cost figures provided by UBA (2012) that had to be adjusted for night and day as well as for heavy and light vehicles. Since long-distance freight transport travels at speeds around 80 km/h, where tyres noise is louder than engine noise, it is assumed that electric vehicles have similar noise levels to ICE vehicles.

Transport safety

Over the past decades, European road transport has experienced tremendous improvements in safety, mainly caused by a number of new technologies, such as driver-assistance programmes and anti-blocking brakes. Since these technologies are continuing to develop at even greater speed, it can be safely assumed that traffic accident rates will continue to drop in the future. Since fatalities and injuries have decreased constantly in the past, it can be estimated that fatalities will decrease by 83 per cent, severe injuries by 71 per cent, and the number of slight injuries will be halved up to 2050.

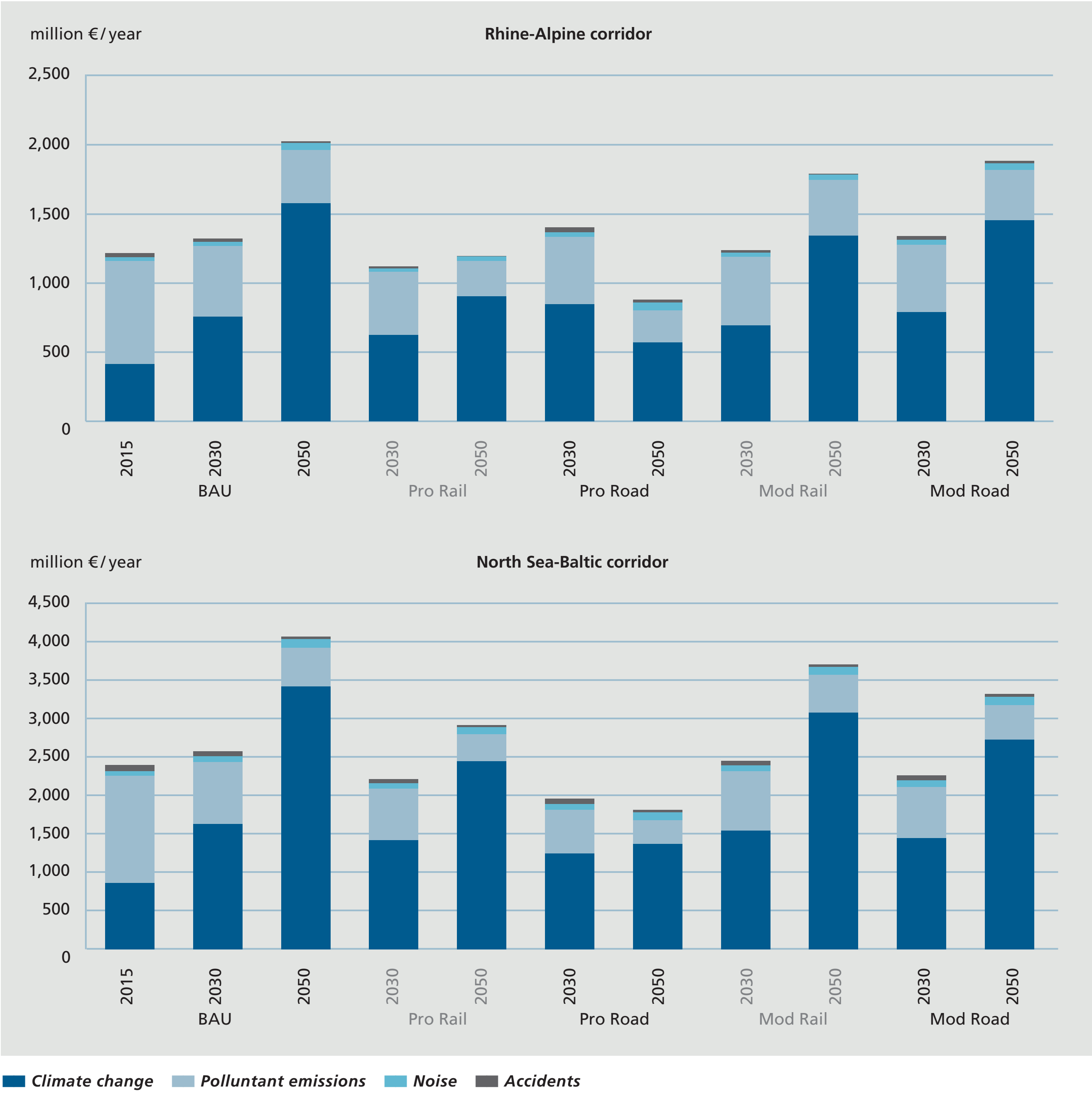
Accidents caused by rail freight are only relevant at railway crossings, where road users are responsible for 90 per cent of them. Rail accidents are disregarded because statistically less than one person per year is killed by freight trains in Germany.

Results on external costs

External costs are primarily determined by the expected strong increase in transport volumes. Total costs increase in the BAU scenario by more than half. In contrast, the Pro Road scenario manages to reduce external costs in 2050 by 42 per cent (RALP) and by 34 per cent (NSB) compared to 2015. This is a remarkable result, because not only road volumes increase during this period, but the costs for CO_2 emissions as well. This reduction is achieved through extensive decarbonisation of road freight. The Pro Rail scenario shows a smaller reduction in road freight emissions, resulting in external costs in 2050 that are similar to the 2015 level. Local air pollution becomes increasingly important.

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

FIGURE 14: External costs by effects



Source: *Fraunhofer ISI*

Comparing the costs in the 2050 scenarios, Figure 13 reveals that all the scenarios reduce the external costs compared to BAU. However, the cost reductions are highest in the Pro Road scenario with a decrease of around 60 per cent, followed by Pro Rail with 40 per cent in the RALP corridor and 27 per cent for the NSB corridor. The lower results in the NSB corridor are due to the larger share of non-electric trucks here. Both moderate scenarios produce only modest improvements between 9 per cent and 20 per cent. External cost reductions in the Pro Road scenario amount to 1.1 billion euros per year on the RALP corridor and to 2.1 billion euros per year in the NSB corridor.

6.4 COST EFFICIENCY

Achieving the massive modal shifts to rail, truck electrification and the resulting deep cuts in carbon emissions requires substantial capital investments in networks and vehicles, as well as structural changes in the transport sectors. In this section, we take a look at the public sector investments needed in the four scenarios. These comprise primarily investments in new capacity, infrastructure upgrades, replacement of infrastructures, and removal of infrastructures (disinvestments) when demand declines. We relate investment costs to the greenhouse gas emissions and external costs saved in each scenario.

Expansion costs in rail networks and their impact on capacity enlargement strongly depend on the actual measures considered.

- *Smaller scale and dedicated bottleneck removals*, such as passing lanes, gap closures, node extension or flyover crossings. These are cost-efficient and can be implemented at relatively short notice, but are limited in scope. For five to eight percentage points of rail market share, studies find 600 to 1,000 euros of annual capital costs per million tkm shifted (cf. Lobig et al., 2016, Holzhey 2010).

- *Substantial capacity extensions* require new track infrastructures, upgraded networks and tunnels for longer, wider, heavier and/or faster freight trains. These investments are costly and require considerable planning and implementation periods. Annual costs per additional ton kilometre to be accommodated in the network deviate widely, but may be taken as 15,000 to 20,000 euros for doubling capacity along major corridors (cf. Holzhey, 2010).

- Digitalisation, automation and the enhancement of intermodal infrastructures. This third category of measures may be large in scope and cost-efficient at the same time. The basic idea here is the better use of the existing capacity of tracks, terminals and trains through booking platforms and intermodal hubs. Studies find annual capital costs of around 1,500 euros per million tkm shifted (cf. Sutter et al. 2016, Lobig et al. 2016).

For massive demand increases in the rail network as considered by the Pro Rail scenario, two effects appear: even more substantial investment costs per tkm due to land scarcity and technical difficulties on the one hand and the merits of digitalisation on the other hand. In a rail-focussed future, we need to exploit both options and therefore take the upper estimate for large-scale capacity expansions in rail infrastructure plus ten per cent for land scarcity: 0.022 €/tkm. In comparison, the German transport infrastructure report for (BMVI 2018) suggests capital investments of 0.043 €/tkm plus 25 per cent running costs without any rail sector organisational reforms.

For road freight transport, we consider two elements of infrastructure expansion: the capacity-driven enlargement of road space for HGVs and the electrification of motorways in the Pro Road scenario. The German federal investment plan arrives at an average cost factor of 0.010 €/tkm with current prices and including 50 per cent running and overhead costs. There is reason to assume road capital costs will rise considerably over time due to land scarcity and regulations. For example, the average construction costs doubled in Germany between 2008 and 2015 (BMVI 2018). However, in order to remain consistent with rail investment estimates, we apply 0.010 €/tkm minus 30 per cent for HGV toll revenues and land scarcity: 0.007 €/tkm from 2015 to 2050.

Catenary infrastructure for hybrid overhead trucks needs to be installed along both corridors in the Pro Road scenario irrespective of the number of HGVs actually using it. Costs are around 2.2 million euros per kilometre along a third of the network, i.e. one million euros per motorway kilometre. With 5 per cent interest, 30 years depreciation and 50 per cent running costs, the total annual costs are 84 million euros for the RALP corridor (1,179 km) and 99 million euros for the NSB corridor to Warsaw (1,227 km). These costs are a substantial factor in the road sector's cost and climate mitigation efficiency.

For inland navigation, we take 50 per cent of the average costs per additional ton-kilometre taken from the German transport infrastructure report (BMVI 2018), because the European river and canal systems still have surplus capacities. For all three modes, we assume 30 per cent of capacity extension costs as disinvestment if traffic volumes shift to other modes.

The results of the cost estimates are shown in Table 7. Comparing the annual costs in 2050 by scenario, we find that the estimated investment and running costs for the Pro Rail scenario are about three to five times higher than the costs needed to accommodate the Pro Road case across all modes.

The table reveals that the savings in external costs justify roughly 60 per cent to 380 per cent annual capital and running costs in the two scenarios. The Pro Rail case is close to a cost-benefit ratio of 1.0, and could exceed this threshold with even more efficient capacity extension measures. This seems particularly possible where rail is strong today, i.e. along the Rhine-Alpine corridor. The Pro Road case far exceeds the benefit-cost threshold of 1.0. This is because the Pro Road scenario directly addresses climate emissions, i.e. the most relevant externality. Its benefits are more obvious where rail is less developed, i.e. in the North Sea-Baltic corridor.

The costs per ton of CO_2 saved are high in both scenarios, but appear less extreme in the Pro Road case compared to the Pro Rail scenario. They range between 108 €/t CO_2-equivalents and 616 €/t CO_2-equivalents, and again the preference for road is more evident on the NSB corridor than along the RALP route. The differences between the two alternatives are, however, not so large as to reject rail-based climate policies completely. We looked at average values under conservative assumptions of infrastructure development costs. These might be very different in specific regions and under different future framework conditions.

TABLE 7: Traffic volumes, costs and cost efficiency indicators 2050 for the Pro Road and Pro Rail scenarios, both corridors

Indicator / transport mode	Unit	RALP		NSB	
		Pro Rail	Pro Road	Pro Rail	Pro Road
Shifted volume in tkm-eq. 2050 relative to BAU					
Road	million tkm/a	–21 576	41 966	–34 071	18 354
Rail	million tkm/a	44 860	–14 962	75 852	12 035
IWT	million tkm/a	–24 507	–37 229	–24 538	–31 427
Annual investment (disinvestment costs)					
Road structures	million €/a	43.9	284.8	69.4	124.6
Road electrification	million €/a		83.5		86.9
Rail network		998.9	99.9	1 689.0	268.0
IWT network	million €/a	88.2	134.1	88.4	113.2
TOTAL	million €/a	1 131.1	602.4	1 846.8	592.6
External costs saved compared to BAU					
Total savings	million €/a	825	1 140	1 153	2 248
Benefit-cost ratio*		73 %	189 %	62 %	379 %
Costs per ton of GHG saved					
GHG emissions saved	Mt GHG/a	2.0	3.5	3.0	5.5
Mitigation costs**	€/t	566	172	616	108

**** External costs saved by total annual investments/disinvestments, ** GHG emissions saved by total annual investments/disinvestments***

***Source**: Fraunhofer ISI*

7 THE FULL PICTURE

7.1 THE SCENARIOS

This report developed and assessed two very different approaches to reaching climate mitigation targets in European freight transport. In the first case, the Pro Rail scenario, we asked how far we could improve the efficiency of the railway system. Across five cost categories and by the year 2050, we found that we can save 66 per cent of production costs per ton-kilometre shipped. Looking at the economic indicators of the railways in the past and extrapolating them to 2050, this saving appears realistic if we look only at major corridors and assume that new technologies and organisational reforms are exploited to their maximum. In the same scenario, we predict that road haulage costs would rise by 25 per cent, mainly driven by drastically increased road infrastructure charges, vehicle technical requirements and labour costs. In fact, the relative costs of road compared to rail would shoot up to 367 per cent, entailing a tripling of rail demand in 2050 compared to business-as-usual. In this scenario, we reduce GHG emissions from around 6.0 to 3.5 Mt CO_2-equivalents on the Rhine-Alpine corridor and from roughly 13.0 to 9.5 Mt CO_2-equivalents on the North Sea-Baltic corridor in 2050.

In contrast to the rail scenario, we also considered the Pro Road scenario, where the emphasis is on decarbonising the road sector and the rail system remains relatively unchanged. This scenario achieves a 95 per cent reduction in the CO_2 emissions of trucks with electrified motorways for hybrid trolley trucks, battery electric and fuel cell solutions, and a mainly carbon-free power sector. This is accompanied by lower energy costs for trucking and a relaxation of motorway charges and vehicle regulations compared to the Pro Rail case. The ton-kilometres increase fivefold by 2050 compared to the BAU scenario. GHG emissions decline more than in the Pro Rail scenario to around 2.0 Mt CO_2-equivalents on the RALP corridor and to just above 5.0 Mt CO_2-equivalents on the NSB route.

7.2 CURBING ROAD EMISSIONS IS INDISPENSABLE

At first glance, these results suggest that climate mitigation in freight transport should be tackled via the road sector. This insight is not surprising because the road sector, even under the very extreme assumptions of the Pro Rail scenario, still carries the lion's share of freight volumes and because the rail sector is largely carbon-free anyway due to its high electrification, efficiency and use of carbon-neutral power. We can therefore conclude that the decarbonisation of freight transport depends on curbing the greenhouse gas emissions of trucking.

Moreover, the emissions from trucks are particularly relevant if we broaden our scope to include transport activities outside the main corridors. Rail has a systemic disadvantage when freight flows are disperse and lower in volume. Bundling does not work in this case and the railway's high share of fixed infrastructure costs cannot be spread across enough consignments to become economically attractive. Network-wide freight flows were not part of this study, but it appears obvious that in this market segment truck energy and climate efficiency constitutes a priority field for climate policy.

7.3 THE CASE FOR STRONG RAILWAYS

Despite the above conclusion, there is still a key role for the railways. Looking at the Pro Rail scenario, we see that focusing on competitive freight railways achieves GHG emission reductions of 42 per cent on the Rhine-Alpine corridor and 27 per cent on the North Sea-Baltic corridor, even though large volumes of freight traffic remain on the roads and the climate efficiency of trucks is not improved. These results obtained with the TRP Transport Chain Model suggest that the highly developed North-South rail infrastructure from the Belgian and Dutch seaports to Northern Italy, i.e. the "Iron Rhine", contributes significantly to rail's potential to drive the carbon neutrality of freight transport.

With rail, we have an existing system, which is already in place, largely electrified and very efficient at moving high quantities of goods. However, this is also a system that has evolved over 200 years and that now requires urgent reforms to overcome its technical, operational and even political stumbling blocks in order to enable it to cope with a tripling of current demand. The current standardisation and digitalisation of control and booking systems across Europe, which is being pushed by the European Commission and the European Railway Agency, needs to be pursued and accelerated. Looking at market trends that show freight growing faster than passenger flows, expensive high-speed projects should be reconsidered in order to free up funds to improve the reliability and capacity of all types of rail services. These extra funds as well as shorter planning and decision procedures should be applied to complete the Iron Rhine and other decisive railway projects in order to fully exploit the sector's potential.

7.4 THE MERITS OF DOING BOTH

Neither of the two extreme scenarios considered here is very likely. Huge investments and a complete re-design of the system are needed for the railway networks to be able to cope with more than the threefold demand relative to the Business-as-Usual case in 2050, or more than ten times today's volumes. Cost estimates are around 2.7 billion euros each year for the two corridors alone. As these sums are hardly feasible, we also calculated moderate (Mod) scenarios for rail and road. These consider "just" half the cost reduction potentials of the respective Pro scenarios. Our assessments show that the impact on climate emissions in both the Mod Rail and Mod Road scenarios are considerably below the fully developed Pro Rail and Pro Road scenarios. The system contains decisive tipping points above which large numbers of shippers start changing their choice of transport mode. The results suggest that drastic measures are required for both road and rail if we want to make a major difference to the climate emissions from transport.

The ability of the trucking sector to become completely carbon-free by 2050 also appears extremely ambitious. We therefore computed two combination scenarios. Starting from the Pro Rail case, we additionally consider the electrification of 50 per cent and 100 per cent of HGV-km in the Pro Rail+50 and Pro Rail+100 scenarios, respectively. The Pro Rail+50 case already achieves very similar GHG emission cuts to the Pro Road scenario in 2050. The full-scale Pro Rail+100 scenario only achieves another 10 per cent reduction in GHG emissions. This finding suggests that we do not need to electrify roads fully if we have a strong and high-capacity rail freight system.

7.5 UNDERESTIMATED POTENTIAL OF SHIPPING

Shipping plays a decisive role on the Rhine-Alpine corridor in particular. The share of inland barges over the different scenarios on the RALP corridor varies considerably between 33 per cent and 64 per cent. On the North Sea-Baltic route, IWT shipping is less relevant than short sea and coastal shipping. Interestingly, the rail scenarios have a larger impact on the market share of barge transport than the road scenarios. This finding is in line with sector studies arguing that the competition between rail and shipping is much more intensive than between road and shipping. IWT and coastal shipping do not face capacity limits and are as climate friendly as freight railways. However, extra efforts are required to combat shipping's air pollution. We conclude that sustainability and climate mitigation strategies on major freight corridors must explicitly consider the potentials and needs of inland and coastal waterway transport.

7.6 CLIMATE CHANGE AND TRANSPORT EXTERNALITIES

The LowCarb-RFC study has a clear focus on climate-friendly freight transport. However, comprehensive sustainability analyses must consider all the externalities that the transport sector imposes on society and nature and convert them to monetary values. This is done by applying the concept of external costs. In this study, we reduced the multitude of potential externalities to five main components: climate change, air pollution represented by nitrogen oxide (NOx) and particulate matter (PM) emissions, noise, and accidents. Using the most recent emission factors and standard assessment methods, we can compute the external costs per year along the corridors. Climate change differs from other externalities as the damage costs per ton of CO_2-equivalents increase strongly over time for two reasons: First, the simplest and cheapest ways to avoid emissions are fully exploited and second, higher concentrations of greenhouse gases in the atmosphere move us closer to climate tipping points. Due to these effects, the role of climate change dominates the externalities towards 2050. While, in 2015, climate change accounts for 30 per cent to 60 per cent of the external costs on the corridors, its share rises to more than 75 per cent in 2050. The other remaining externalities are mainly air pollution, dominated by particle emissions from power plants, tyres and brakes, plus a minor contribution of accidents and noise. NOx emissions and transport safety will no longer be significant in 2050 thanks to driver-assistance and safety systems in vehicles and advanced fuels, electrification and motor control systems.

7.7 CONCLUDING REMARKS

We can summarise the conclusions from this work as follows:

- Rapid decarbonisation of road transport through electrification is indispensable to achieve the climate targets in transport.

- Strong railways are needed to achieve even deeper cuts in GHG emissions and compensate those segments of road haulage that cannot be electrified. The sector needs to standardise and simplify technologies and operations.

- Inland waterway and coastal shipping need to play an integral role in decarbonisation strategies as they still have available capacities and a small carbon footprint.

- Sustainability considerations will probably focus on greenhouse gas emissions as their economic costs increase and because other externalities can and will be mitigated technically.

- If all measures were implemented, we can achieve up to 70 per cent reduction in GHG emissions of freight transport along major European corridors. Combining road and rail measures achieves the highest mitigation results.

- The annual investment costs required are huge, ranging between 1.2 billion euros per year for decarbonising road transport to three billion euros for a massive modal shift from road to rail and inland waterway transport.

- CO_2 mitigation costs then range from 570 euros per ton for decarbonising road to 172 euros per ton for massive shifts to rail. The costs of decarbonising the energy sector are excluded here.

These results clearly indicate what a huge undertaking it is to decarbonise the European long-distance freight sector. Cheaper and quicker options are badly needed, funding issues must be solved and decision pathways need to be drastically accelerated to achieve our 2030 and 2050 targets.

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