Capacity for Rail

Towards an affordable, resilient, innovative and high-capacity European Railway System for 2030/2050

Assessment of technologies, scenarios and impacts

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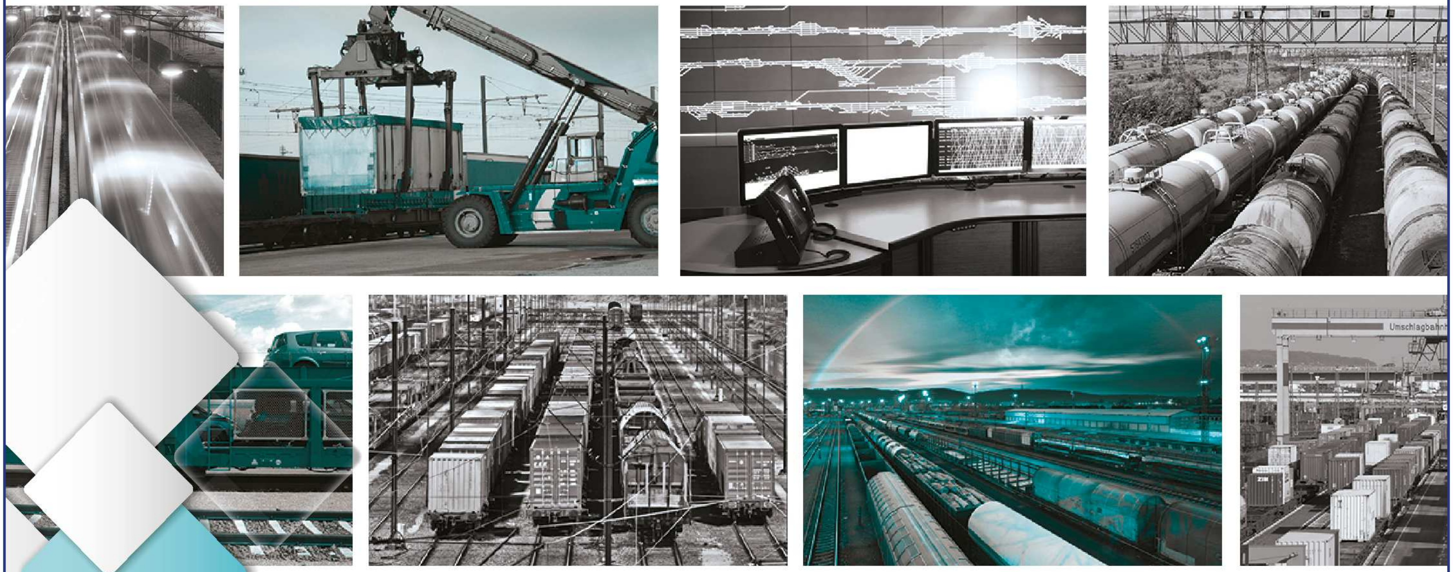

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Acronyms and Abbreviations

The following list provide definitions for acronyms and abbreviations and for terms used in this document:

Base year	Year 0 in the time horizon of CBA, reference year for prices and unit costs
CBA	Cost-Benefit Analysis
Demand Elasticity	Multiplicative factor in an assumed linear model for the relationship between traffic demand and other variable
EC	European Commission
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IMs	Infrastructure managers
IRR	Internal Rate of Return
LCC	Life-Cycle Costs
MCA	Multi-Criteria Analysis
NPV	Net Present Value
p·km	Passenger km
RAMS	Reliability, Availability, Maintainability and Safety
SE Matrix	Stakeholder Effects Matrix
SP	Sub-project
T·km	Ton km
TEN-T	Trans-European Transport Networks
Traffic Mix	Composition of different vehicle types by percentage in number of vehicles in a given section
Train load	Freight train with a single type of cargo
TRL	Technology Readiness Level
Wagon load	Freight train combining wagons with its own type of cargo
WP	Work Package

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Executive Summary

A Cost-Benefit Analysis (CBA) based on a tool developed in Task 5.4.1 was performed for two case studies.

The first case study is built on the Swedish sections of the Scandinavian-Mediterranean TEN-T Corridor. Both rail and road corridor sections are modelled with input data about infrastructure, operation and traffic forecasts. The analysis is made through a set of Scenarios where different sets of C4R Innovations, operational or market conditions changes are modelled.

The first scenario (Scenario 1) includes the implementation of all C4R innovations throughout the Swedish rail network, as well as increases in train length up to 1500 m. The CBA results in a negative NPV, with the large investment not being offset by the producer surplus generated by the modal transfer. When the Scenario is altered to include a very significant reduction in delays, this is enough to turn the NPV positive.

Two scenarios (2 and 3) are built with a more limited implementation of infrastructure innovations, mainly slab track. The results show an improvement relative to Scenario 1, showing the advantages of a more selective approach.

A Rail Positive Scenario (4) assumes a full migration to innovative freight wagons, including automatic couplers and EP brakes, leading to further operating costs reductions and a small speed increase. This scenario has the most positive results of all that were tested.

In order to test how some of the expected innovations in road transportation would affect the profitability of the investment in the rail sector being tested, Road Positive Scenarios (5 and 6) were also tested. These assume an increase in road truck gross weight and reductions in operating costs. The results show the benefits that were present in Scenario 1 from modal transfer may be virtually obliterated. We also tested how the introduction of taxes on road transportation can partially offset these effects, boosting the rail sector.

A second case study was based on a more detailed analysis of a smaller corridor section in southern France (Montpellier-Perpignan) that was performed in the context of the Demonstrations for Deliverable 5.5.6. This corridor section has the further feature of being a bottleneck in the wider corridor it is inserted in.

A comparable set of scenarios was analysed for this corridor section showing overall positive results in terms of NPV, even for the ones with heavier investment. However, the relative changes between the different scenarios are not qualitatively different from the ones obtained in the first case study.

The results of the Montpellier-Perpignan case study in comparison with the Swedish one show how the kind of deep investment in infrastructure is more easily profitable in capacity constrained sections, even if this profitability hangs on an assumed increase in availability.

Both case studies show how improvements in operation leading to longer, higher capacity trains can have very positive impacts with relatively modest investments.

1 Background

This document is produced as part of Tasks 5.4.2 and 5.4.3 of the Capacity4Rail (C4R) project Sub Project (SP) 5. The assessment of technologies and scenarios and their ranking, immediately follow the work developed in Task 5.4.1 to develop the methodologies for this assessment.

In Task 5.4.1, and as reported in the corresponding deliverable, D5.4.1, two complementary methodologies were considered for the assessment of the technologies and scenarios. A Cost-Benefit Analysis (CBA) would be supplemented by a Multi-Criteria Analysis (MCA) that would help take into account non-economic aspects that are usually not captured in a CBA. Ultimately, it was decided that the MCA would be performed in the context of SP3.

The CBA to be performed in the context of this task has some particularities that were already discussed at length in D5.4.1 and are mainly connected to the wide geographical scope of the analysis and the potential lack of specific information and data on the innovations to be assessed.

2 Case Study 1: Swedish sections of Scandinavian-Mediterranean Corridor

2.1 OVERVIEW

2.1.1 CASE STUDY DESCRIPTION

In the present study, we will perform a Cost-Benefit Analysis (CBA) of the implementation of several innovations in the Swedish portion of the Scandinavian-Mediterranean TEN-T Corridor, illustrated here by the map in Figure 1.

For this analysis, the considered sections of the Swedish network are presented in Table 1 and Table 2.

This case study focuses almost exclusively on freight, since it is also the sector where most of the effects of the C4R innovations are aimed at. Passenger traffic is also modelled but is kept constant throughout the analysis, as well as costs and other indicators on the passenger side.

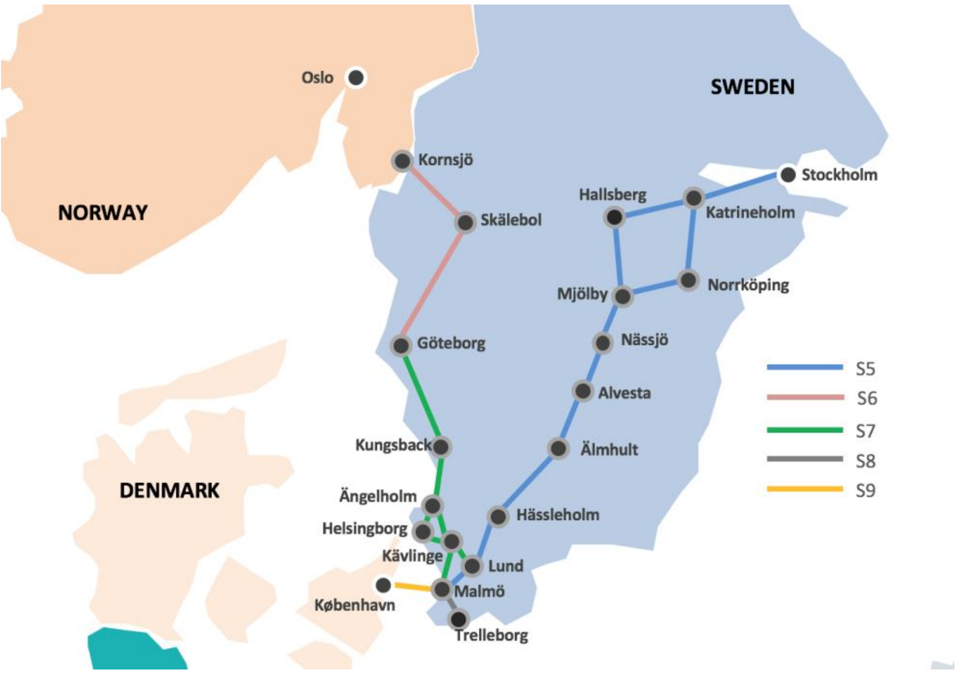

Figure 1. Swedish sections of Scandinavian-Mediterranean Corridor

Table 1. Swedish Rail Network sections that are part of the Scandinavian-Mediterranean Corridor

Rail Corridor Segmentation					
S5	Stockholm - Katrineholm	**S5**	Nässjö - Alvesta	**S7**	Kungsbacka - Ängelholm
S5	Katrineholm - Hallsberg	**S6**	Alvesta - Lund	**S7**	Ängelholm - Kävlinge via Helsingborg
S5	Katrineholm - Norrköping	**S5**	Lund - Malmö	**S7**	Ängelholm - Kävlinge via Åstorp
S5	Norrköping - Mjölby	**S6**	Oslo - Halden	**S7**	Kävlinge - Lund
S5	Hallsberg - Degerön	**S6**	Halden - Öxnered	**S7**	Kävlinge - Malmö
S6	Degerön - Mjölby	**S6**	Öxnered - Göteborg	**S8**	Malmö - Trelleborg
S5	Mjölby - Nässjö	**S7**	Göteborg - Kungsbacka	**S9**	Malmö - København

TABLE 2. SCANDINAVIAN-MEDITERRANEAN CORRIDOR'S SWEDISH ROAD NETWORK SECTIONS

Road Corridor Segmentation					
S5	Stockholm - Helsingborg (E4)	**S6**	NO border - Gotebörg (E6)	**S8**	Malmö - Trelleborg (E22)
S5	Helsingborg - Malmö (E20)	**S7**	Göteborg - Helsingborg (E20)	**S9**	Malmö - København (E20)

2.1.2 CBA INVESTMENT LEVELS

The CBA evaluates different scenarios including different sets of C4R innovations, as well as some changes to boundary conditions. In each scenario, the net costs and benefit are computed from the comparison of two investment levels:

- **'Baseline and TEN-T'**, which considers the system's current conditions, in terms of infrastructure characteristics, rolling stock, or maintenance costs, for instance. These conditions will change upon the implementation of TEN-T projects.
- A **C4R Scenario**, which assumes the implementation of a given set of C4R innovations.

In each investment level both investment costs and parameters are set to the assumed values, as discussed in the following section. The main scenario, described as follows, which we call **C4R Scenario 1 (All)** assumes the implementation of all considered innovations in all sections of the rail network. All other scenarios follow the same pattern, always using Scenario 1 as a base upon which changes are introduced.

2.2 INPUT DATA FOR C4R SCENARIO 1 (ALL)

2.2.1 REFERENCE VALUES

In this section, we will discuss the CBA parameters for CBA Scenario 1, many of which are common to all tested scenarios.

Regarding the analysis boundaries, the following values were used:

- 40-year time horizon with 2015 as base year and 2016 as "year 1";
- Financial and social discount rates of 4%;
- Shadow price conversion factor of 0.95.

The time horizon, discount rates and conversion factor are within the typical bounds set by the EC Guidelines [1] and also recommended for long lasting assets in the guideline for LCC and RAMS Analysis [2].

Since this analysis is focused on the impacts of innovations on freight transportation, a considerable attention was dedicated to its modelling. The CBA tool models the traffic based on a set of reference trains and the fraction of traffic each represents, what we otherwise call the "traffic mix".

A set of five train types corresponding to market segments is considered for each investment level. These reference trains were obtained from expert judgement with contributions from SP2, as documented with detail in the Appendix to this deliverable, 'Parameters for capacity and costs of freight trains in Sweden including MS23 Business cases and validation of new freight wagons'. Their main characteristics are summarized in Table 3 to Table 5. Once the TEN-T projects are complete, it is assumed that trains with up to 750 m in length will be able to run through every section of the network, with the adequate estimated changes in the remaining figures. Likewise, the definition of the reference train for the C4R Scenario assumes that trains with up to 1000 m will be running in the network. This will lead to a higher cargo capacity per train, reducing operating costs and greenhouse gas emissions.

Table 3. Reference freight trains for the Swedish case study Baseline.

Baseline

	Train Load	Wagon Load	IM Container	IM Trailer	WL Feeder
Length (m)	600	500	630	630	250
Tare Weight (T)	555.4	450.8	460.3	589.7	239.6
Axle Load (T/axle)	17.9	16.4	16.1	16.3	13.6
Cargo Capacity (T)	1100	949	899	1300	450
Average Load Factor[1]	50%[2]	55%	50%	53%	45%
Average Load (T)	550	522	450	689	203
Average Gross Weight (T)	1105	973	910	1279	442
Operating Costs [€/(T·km)]	0.0162	0.0168	0.0219	0.0149	0.0287
Terminal Costs [€/(T·km)]		0.0155	0.0141	0.0155	
Tax [€/(T·km)]		0.0015	0.0025	0.0028	
GHG Emissions [kg/(T·km)]	0.0029	0.0029	0.0032	0.0024	0.0055

Table 4. Reference freight trains for the Swedish case study after TEN-T investments, available from 2020.

Baseline after TEN-T Investment (from 2020)

	Train Load	Wagon Load	IM Container	IM Trailer	WL Feeder
Length (m)	732	738	735	726	741
Tare Weight (T)	662.8	631.2	524.7	448.6	566
Axle Load (T/axle)	17.9	16.4	16.1	16.3	13.6
Cargo Capacity (T)	1354	1424	1056	1506	1433
Average Load Factor	50%	55%	50%	53%	45%
Average Load (T)	677	783	528	798	645
Average Gross Weight (T)	1340	1414	1053	1247	1211
Operating Costs [€/(T·km)]	0.0145	0.0142	0.0203	0.0139	0.0146
Terminal Costs [€/(T·km)]		0.0155	0.0141	0.0155	
Tax [€/(T·km)]		0.0015	0.0025	0.0028	
GHG Emissions [kg/(T·km)]	0.0025	0.0022	0.0029	0.0021	0.0025

Table 5. Reference freight trains for the Swedish case study after C4R Innovations in Scenario 1.

C4R Scenario 1

	Train Load	Wagon Load	IM Container	IM Trailer	WL Feeder
Length (m)	997	997	998	981	986
Tare Weight (T)	877.6	828	685.7	579	729.2
Axle Load (T/axle)	17.9	16.4	16.1	16.3	13.6
Cargo Capacity (T)	1861	1942	1447	2053	1925
Average Load Factor	50%	55%	50%	53%	
Average Load (T)	931	1068	723	1088	866
Average Gross Weight (T)	1808	1896	1409	1667	1595
Operating Costs [€/(T·km)]	0.0125	0.0127	0.0177	0.0124	0.0129
Terminal Costs [€/(T·km)]		0.0155	0.0141	0.0155	
Tax [€/(T·km)]		0.0015	0.0025	0.0028	
GHG Emissions [kg/(T·km)]	0.0020	0.0018	0.0024	0.0017	0.0021

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[1] Average load factors take into account empty returns and partially loaded trains.

TABLE 6. REFERENCE ROAD FREIGHT VEHICLES FOR THE SWEDISH CASE STUDY

	Baseline	After TEN-T	Low-cost 1	Low-cost 2	Future SE	European
Maximum Load (T)	40	43.5	40	43.5	50	26
Average Load Factor	60%	60%	60%	60%	60%	60%
Average Load (T/vehicle)	24	26.1	24	26.1	30	15.6
Operating Costs [€/(T·km)]	0.0508	0.0475	0.0292	0.0318	0.0433	0.0712
Tax [€/(T·km)]	0.0121	0.0115	0.0117	0.0069	0.0107	0.0160
GHG Emissions [kg/(T·km)]	0.0320	0.0310	0.0320	0.0310	0.0290	0.0420

A similar exercise was performed with relation to road freight transportation, with five types of vehicles provided by SP2 partners, as summarized in Table 6.

Concerning freight value of time, we know that the average value of freight travelling on the roads is significantly higher that travelling on the railways. In this case, we assumed that the diverted traffic has the same value of time as existing rail freight traffic. The reasoning behind this decision is that, since road freight has a higher average value, the first freight to be diverted to rail, due to decreasing costs, is the lowest value freight travelling on the roads.

The value of time was established as:

- 1.66€/h for rail freight, including freight diverted from road to rail
- 4.05€/h for road freight

Despite the preceding argument, the figure considered for the diverted freight from road to rail is a lower bound taken in the absence of more detailed data. The effect of this assumption is to underestimate the savings in Value of Time arising from modal transfer. So, it is a conservative estimate.

Although innovations in passenger transportation are not taken into account in this analysis, passenger traffic still needs to be modelled.

Since most innovations to be implemented relate to freight transport, the same reference passenger train was used for all investment levels with the following values:

- Tare weight: 348 T;
- Maximum axle load: 17.5 T/axle;
- Number of offered seats: 250;
- Average load factor: 45%
- Average operating cost: 0.1 €/(p·km);
- Average CO2 emission: 0.02 kg/(p·km).

We also need to set reference road vehicles, specifically, with their average load, average operating costs and greenhouse gas emissions. Once again, the adopted values were set with resort to expert judgement. As for the trains, we considered only one type of passenger road vehicle with the following characteristics:

- Average load: 1,21 passengers/car;
- Average operating costs: 0.35 €/(p·km);
- Average CO_2 emission: 0.1 kg/(p-km)

In the case of passenger value of time, these are typically divided into business, leisure and commuter passengers; each of these has a different valuation of travel time. In this study, we considered the following traffic mix:

- Business: 50% of passengers – Value of time: 30€/h [3];
- Leisure: 40% of passengers – Value of time: 10€/h [3];
- Commuter: 10% of passengers – Value of time: 15€/h [3];
- Average value of time (for both road and rail passengers): 22€/h[3],

Finally, in the valuation of externalities, only greenhouse gas emissions are considered. An emission cost of 0.031€/kg was considered for the base year, 2015, and a constant yearly growth of 0.001€/kg of CO_2 is assumed.

2.2.2 INFRASTRUCTURE DATA

The 2016 Swedish Network Statement [3] provides much of the required information to fill the fields on the 'Infrastructure Data' sheet, namely, section lengths, number of tracks, average travel times for freight and passenger trains, and infrastructure access charges. These figures have been validated and corrected by the partners. In the case of maintenance costs, switch density, buffer times, and supplements for maintenance, the considered values are presented in Table 7.

2.2.3 TRAFFIC DATA

The TEN-T report on the Scandinavian-Mediterranean corridor [4] includes a set of traffic projections. Although this data does not cover the entire corridor and is not presented uniformly, it includes projections for all Swedish sections of roads and rail in terms of trains and road vehicles per day. The baseline traffic scenario is set from this data through linear interpolation for the base year. The resulting values are listed by section in Table 8 for rail and Table 9 for road.

During the CBA horizon, the rail demand is expected to grow according to each of the scenarios' performance. This variation will respond to the elasticity of the demand to a set of parameters to be evaluated:

- Annual GDP Growth: 1.5%;
- Freight Demand Elasticity with GDP: 1;
- Freight Demand Elasticity with Operating Costs: -0.42.

Since passenger traffic is kept constant throughout the analysis period, its elasticities are set at 0.

2.2.4 INVESTMENT SCENARIO

As already mentioned the analysis of each scenario is based on the incremental comparison of two investment levels. Specifically, for the first scenario of this case study we have:

- a **Baseline and TEN-T** including the investments needed for the maintenance of current conditions, as well as the already planned TEN-T projects;
- **C4R Scenario 1 (All)** where all the main innovations of the project are considered along the entire network of the case study.

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[3] Values taken from HEATCO study, Euros/2002 (no escalation considered)

Table 10 and Table 11 summarize the proposed interventions for the considered investment scenarios.

TABLE 7. REFERENCE VALUES FOR THE INFRASTRUCTURE IN THE BASELINE

Parameter	Baseline Value	
Maintenance Costs	Fixed	Variable
Track, Signaling and Elect.	15,600 €/(year·km)	309 €/(MGT·km)
Switches and Crossings (S&C)	1,845 €/(year unit)	193 €/(MGT·unit)
Switch Density	0.14/km	
Buffer times and Crossing Buffer	5% of travel time	
Supplement for Track Maintenance	5h	

TABLE 8. RAIL TRAFFIC PROJECTIONS FOR THE BASELINE YEAR (2015)

Rail Traffic Baseline Forecast

	Section	Year	Passenger trains per day	Freight trains per day
S5	Stockholm - Katrineholm	2015	116	46
S5	Katrineholm-Hallsberg	2015	112	31
S5	Katrineholm-Norrköping	2015	38	47
S5	Norrköping-Mjölby	2015	270	49
S5	Hallsberg - Degerön	2015	20	59
S6	Degerön - Mjölby	2015	36	59
S5	Mjölby - Nässjö	2015	116	96
S5	Nässjö-Alvesta	2015	82	93
S6	Alvesta-Lund	2015	112	122
S5	Lund - Malmö	2015	480	141
S6	Oslo-Halden	2015	10	26
S6	Halden-Öxnered	2015	10	32
S6	Öxnered-Göteborg	2015	196	48
S7	Göteborg - Kungsbacka	2015	262	35
S7	Kungsbacka-Ängelholm	2015	150	37
S7	Ängelholm - Kävlinge via Helsingborg	2015	50	124
S7	Ängelholm - Kävlinge via Åstorp	2015	124	50
S7	Kävlinge - Lund	2015	174	174
S7	Kävlinge - Malmö	2015	174	30
S8	Malmö - Trelleborg	2015	76	33
S9	Malmö - København	2015	228	46

TABLE 9. ROAD TRAFFIC PROJECTIONS FOR THE BASELINE YEAR (2015)

Road Traffic Baseline Forecast

	Section	Year	Passenger cars per day	Freight trucks per day
S5	Stockholm - Helsingborg (E4)	2015	13156	3915
S5	Helsingborg - Malmö (E20)	2015	38270	7056
S6	NO border - Gotebörg (E6)	2015	21158	2650
S7	Göteborg - Helsingborg (E20)	2015	17577	4346
S8	Malmö - Trelleborg (E22)	2015	11060	3087
S9	Malmö - København (E20)	2015	18823	2106

TABLE 10. SCHEDULING OF ALL INTERVENTIONS TO BE PERFORMED IN THE 'BASELINE AND TEN-T' SCENARIO

Section		Renewals		Signaling	New lines		Other interventions	
		Track	S&C	ERTMS Implementation	Double track	Four track	Passenger stations	Other
S5	Stockholm - Katrineholm	2030	2030	2015-2027		2030		2020-2025 (Bottleneck in Stockholm)
S5	Katrineholm-Hallsberg	2030	2030	2015-2027		2030		
S5	Katrineholm-Norrköping	2030	2030	2015-2027		2030		
S5	Norrköping-Mjölby	2030	2030	2015-2027		2030 (Norrköping-Linköping)		
S5	Hallsberg - Degerön	2030	2030	2015-2027	2015-2019			
S6	Degerön - Mjölby	2030	2030	2015-2027				
S5	Mjölby - Nässjö	2030	2030	2015-2027				
S5	Nässjö-Alvesta	2030	2030	2015-2027				
S6	Alvesta-Lund	2030	2030	2015-2027	2020-2025 (Hässelholm-Lund)	2020-2025 (Hässelholm-Lund)		
S5	Lund - Malmö	2030	2030	2015-2027	2020-2025 (Lund-Arlöv)			
S6	Oslo-Halden	2030	2030	2015-2027				
S6	Halden-Öxnered	2030	2030	2015-2027				
S6	Öxnered-Göteborg	2030	2030	2015-2027			2015 (Göteborg: signalbox)	2017-2025 (track system at Olskskroken)
S7	Göteborg - Kungsbacka	2030	2030	2015-2027				
S7	Kungsbacka-Ängelholm	2030	2030	2015-2027				
S7	Ängelholm - Kävlinge via Helsingborg	2030	2030	2015-2027	2020-2025 (Ängelholm-Maria)			
S7	Ängelholm - Kävlinge via Åstorp	2030	2030	2015-2027			2017-2019 (Ärlov-Teckomatorp: new stations)	2017-2019 (Ärlov-Teckomatorp: expansion of sidings, modern signaling systems)
S7	Kävlinge - Lund	2030	2030	2015-2027				
S7	Kävlinge - Malmö	2030	2030	2015-2027				
S8	Malmö - Trelleborg	2030	2030	2015-2027	2015-2016		2015-2016 (new stations)	
S9	Malmö - København	2030	2030	2015-2027				

Table 11. Scheduling of all interventions to be performed in the C4R Scenario

Section	Renewals			Signaling	New lines		Other interventions		Innovations			
	Track	S&C	Upgraded interchange	ERTMS Implementation	Double track	Four track	Passenger stations	Other	Slab track	S&C	Monitoring Systems	Freight Rolling Stock
S5 Stockholm - Katrineholm			2025 (Stockholm Årsta, and Stockholm North Rosersberg)	2015-2027		2030		2020-2025 (Bottleneck in Stockholm)	2025	2025	2025	2025 (Maximum 25t/axle, modern coupling, braking, and intelligence)
S5 Katrineholm-Hallsberg				2015-2027		2030			2025	2025	2025	
S5 Katrineholm-Norrköping				2015-2027		2030			2025	2025	2025	
S5 Norrköping-Mjölby				2015-2027		2030 (Norrköping-Linköping)			2025	2025	2025	
S5 Hallsberg - Degerön				2015-2027	2015-2019				2025	2025	2025	
S6 Degerön - Mjölby				2015-2027					2025	2025	2025	
S5 Mjölby - Nässjö				2015-2027					2025	2025	2025	
S5 Nässjö-Alvesta				2015-2027					2025	2025	2025	
S6 Alvesta-Lund				2015-2027	2020-2025 (Hässelholm-Lund)	2020-2025 (Hässelholm-Lund)			2025	2025	2025	
S5 Lund - Malmö				2015-2027	2020-2025 (Lund-Arlöv)				2025	2025	2025	
S6 Oslo-Halden				2015-2027					2025	2025	2025	
S6 Halden-Öxnered				2015-2027					2025	2025	2025	
S6 Öxnered-Göteborg			2025 (Göteborg Gullbergvass, and Göteborgs Hamm)	2015-2027			2015 (Göteborg: signalbox)	2017-2025 (track system at Olskskroken)	2025	2025	2025	
S7 Göteborg - Kungsbacka				2015-2027					2025	2025	2025	
S7 Kungsbacka-Ängelholm				2015-2027					2025	2025	2025	
S7 Ängelholm - Kävlinge via Helsingborg				2015-2027	2020-2025 (Ängelholm-Maria)				2025	2025	2025	
S7 Ängelholm - Kävlinge via Åstorp				2015-2027			2017-2019 (Ärlov-Teckomatorp: new stations)	2017-2019 (Ärlov-Teckomatorp: expansion of sidings, modern signaling systems)	2025	2025	2025	
S7 Kävlinge - Lund				2015-2027					2025	2025	2025	
S7 Kävlinge - Malmö				2015-2027					2025	2025	2025	

S8	Malmö - Trelleborg			2025 (Trelleborg Kombiterminal Öst)	2015-2027	2015-2016		2015-2016 (new stations)		2025	2025	2025	
S9	Malmö - København			2025 (København Malmö port, and Malmö Kombiterminal)	2015-2027					2025	2025	2025	

Baseline and TEN-T Projects

The baseline considers the investment on track and switches and crossings renewal. For this study, it was assumed that planned renewals are staggered along the first 15 years of the analysis, with 25% of them taking place in 2020 (year 5), another 25% in year 10 (2025) and the remaining 50% in year 15 (2030). The considered unit costs are 500 000 €/km for the renewal of single ballasted track, and 300 000 €/unit for the replacement of a switch and crossing.

In addition to these renewals, a set of investments listed in the TEN-T corridor report [4] are also considered. These projects aim to implement the TEN-T objectives for the rail network, namely, allow the circulation of trains up to 750 m and with an axle load of 22,5 T/axle, full electrification, implement ERTMS, allow freight trains to run at 100 km/h line speeds.

The list of projects in the TEN-T report includes cost estimates and time frame for each project. Only projects concerning upgrade of existing lines were included in the analysis.

C4R Scenario 1 (All)

The main innovations considered as part of the C4R scenario are the following:

- new slab track (WP1.1);
- new switches and crossings (S&C) with enhanced tolerance to failure and higher availability leading to less delay minutes (WP1.3);
- new freight wagons with higher axle loads, 25 T/axle (WP2.2.);
- terminal upgrades (WP2.3);
- new monitoring systems (WP4.3, WP4.4).

Several different scenarios may be built with different combinations of these innovations. In this study, we consider a scenario where the slab track, the monitoring systems, the switches and crossings, and the rolling stock innovations will be concluded in 2025 and are immediately implemented in the entire section of the network under analysis.

The construction of the C4R Scenario assumes that the Baseline and TEN-T interventions, apart from the track and switches and crossings renewals, have already been implemented. Each one of the proposed innovations will have a specific effect on the different variables and, possibly, combination effects with other innovations.

The investment cost of upgrading to slab track is assumed to be 1.000.000 €/(km track), which is within the typical frame of values for existing slab track designs; this value includes the installation of innovative monitoring systems, as complement to the track's replacement. The main intended effect from the implementation of slab track is the reduction of maintenance costs and the increase of availability. We thus assume a 34 % reduction in variable maintenance costs for the track and 27% reduction for S&C wherever the track was upgraded to slab technology.

Although not analysed in this case study, there are other possible improvements, outside the scope of C4R innovations for track and S&C to the E5 standard (DB requirements, AK 25T), like for example:

- Rail type at least 60 kg/m on main line, 54 kg/m on secondary lines (est. 380 €/ track m);
- Rebuilding S&C with 49kg/m rail in 54 kg/m (est. 315 T€/unit);
- Check/guide rail support in switches (est. 9500 €/unit);
- Analysis of bearing capacity of bridges, if not build for 25 t axle load (E5) (individual costs);
- Analysis of bearing capacity of embankments (individual costs).

Regarding S&C, installation cost is estimated to be 1.5 times the current average value, 150,000 €/unit; as for the slab track innovation, monitoring systems will also be available for S&C, their installation cost already included in the switches and crossings installation value. The introduction of advanced monitoring system will contribute for a reduction in fixed maintenance costs, the overall performance of the new system leading to a reduction of S&C maintenance costs to approximately a third of that of the baseline value and will reduce the delay minutes caused by S&C by 50%.

It is often assumed that the implementation of slab track is a prerequisite for the operation of the new 25 T/axle wagons. However, one can consider some scenarios where wagon replacement is not combined with the upgrade to slab track. In this case, maintenance costs would increase, according to some models, by a factor equal to the square of the ratio between the new axle load and the existing one, *i.e.*, (25/22.5).

Although terminal upgrades are not considered for this C4R scenario, they may be assessed in alternative configurations. For these cases, a freight terminal upgrade cost of 100 M€/terminal may be assumed. The benefits are, however, difficult to estimate at this stage. Surely, the benefits from this innovation are related to the operating costs: one of the main effects of the upgrade for the terminal would be quicker loading and unloading operations. In the absence of detailed information, a reduction of the operating costs of freight rail transport in the order of 10% is assumed as a consequence of terminal upgrades. Quicker loading and unloading operation also mean a reduction of freight trains travel time, assumed to be in the order of 5%.

To summarize, the main effects of each innovation are listed in Table 12.

TABLE 12. SUMMARY OF C4R INNOVATION EFFECTS

Innovations	Effects
Slab track and Monitoring Systems	34% reduction of variable maintenance costs for the track 60% reduction of unplanned unavailability (when combined with new S&C)
Switches and Crossings	27% reduction of variable maintenance costs for S&C 60% reduction of unplanned unavailability (when combined with slab track)
New freight wagons	Increase of track variable maintenance costs by the factor $(25/22{,}5)^2$ in case of no upgrade to slab track or improved ballasted track
Upgrade of Terminals	10% reduction of operating costs of freight railway transport 5% reduction of freight trains travel time compared to TEN-T scenario

Regarding the evolution of the rolling stock characteristics with the implementation of innovations in the considered scenarios, we adopted the following trains for the Rail Freight:

- From 2015 to 2019 – all trains are chosen from the initial reference trains, as described in Table 3.
- From 2020 onwards – with the implementation of TEN-T projects, all trains will increase their length to 750m.
- Implementation of C4R Scenario 1 (All) – when C4R innovations are implemented, it is assumed that 50% of trains will increase their length to 1000m.

The considered Rail Freight Traffic mix for each section, and in each of these periods, may be consulted in Table 34, Table 35 and Table 36, presented in the Appendix, at the end of this document.

For the Road Freight Traffic mix scenario, the figures in Table 13 were considered:

TABLE 13. ROAD TRAFFIC MIX FOR SCENARIO 1 (ALL); REFERENCE ROAD FREIGHT VEHICLES ARE LISTED IN TABLE 6.

Reference Vehicle	All Scenarios (From 2016 to 2029)	C4R Scenario 1 (All) (From 2030)
Baseline	40%	10%
After TEN-T	10%	40%
Low-Cost 1	0%	0%
Low Cost 2	0%	0%
Future SE	0%	0%
European	50%	50%

2.3 RESULTS FOR SCENARIO 1 (ALL)

2.3.1 COST-BENEFIT ANALYSIS

The results for Scenario 1, with all innovations implemented in all sections, as described in the preceding sections, are summarised in Table 14.

The first item that stands out is the large increase in investment with respect to the Baseline and TEN-T, although a portion of it is offset by the reduction in maintenance costs brought by the implementation of slab track and the new switches and crossing.

The main effect of the changes introduced in this scenario is reduction in total road freight operating costs and a corresponding, albeit lower, increase on the rail freight operating costs due to modal transfer. This transfer of traffic from road to rail is made possible by the increase in capacity on the rail side. This dominance of the net consumer surplus is shown in Figure 2.

The capacity increase of the rail corridor is the result of two simultaneous effects. On the one hand, there is an increase in the capacity of each train arising from greater train lengths. On the other hand there is a greater availability of the infrastructure due to shorter closing times for maintenance allowed by the slab track. Simply from the inspection of the results in Table 14, one cannot discriminate these two effects. However, the capacity occupation computations provided by the CBA tool indicate that the increase in train capacity is enough to absorb the surplus demand that would otherwise need to travel by road due to shortage of capacity. It is also worth noting that this model keeps load factors constant, leaving a very significant potential for capacity gains from a more efficient load management untapped.

The net benefit generated by the modal transfer, in the producer surplus category, is the result of a lower unit operating cost of rail transportation. It is thus expected that variations in these unit operating costs have a major effect on the final result, as we shall see in some of the alternative scenarios.

There is also a significant net benefit coming from the reduction in greenhouse gas emissions from the transfer of traffic from road to rail, although the figures involved are at least one order of magnitude bellow the value of operating costs. The relative difference between the modes is, however, much more marked.

Finally, the value of time contributes with a negative net benefit due to slightly lower average speeds assumed for freight trains with relation to freight vehicles travelling by road. We recall that we used the lower bound for the unit value of time of the transferred cargo. Still, the figure is also one order of magnitude bellow the changes in operating costs.

The overall NPV is negative, but it is also roughly one order of magnitude below the increment in investment relative to de Baseline and TEN-T and the changes in operating costs. We should stress again that, given the wide scope of this analysis, one should not draw too strong conclusions from specific absolute values, but instead focus on a more qualitative analysis and attempt to understand the mechanisms at work, as this discussion attempts to do.

All figures related to passengers are null since all related inputs were kept constant and the effect of delays shall be analysed separately.

TABLE 14. CBA RESULTS FOR IMPLEMENTATION OF SCENARIO 1 IN THE SWEDISH SECTION OF THE SCANDINAVIAN-MEDITERRANEAN CORRIDOR.

	Net Costs
	Scenario 1 vs 'Baseline and TEN-T'
Investment	765 367 260 €
Maintenance	-136 828 801 €
Total Financial Cost	**628 538 459 €**
Total Economic Cost	**597 111 536 €**

	Net Benefits
	Scenario 1 vs 'Baseline and TEN-T'
Consumer Surplus	
Value of Time	
Passenger Time Savings	0 €
Freight Time Savings	-122 824 385 €
Delays	0 €
Producer Surplus	
Rail Passenger Operating Costs	0 €
Rail Freight Operating Costs	-1 389 778 994 €
Road Passenger Operating Costs	0 €
Road Freight Operating Costs	1 829 476 278 €
Externalities	
Rail Passenger GHG Emissions	0 €
Rail Freight GHG Emissions	-1 258 931 €
Road Passenger GHG Emissions	0 €
Road Freight GHG Emissions	52 117 400 €
Total Economic Benefits	**367 731 368 €**

NPV	**-229 380 168 €**

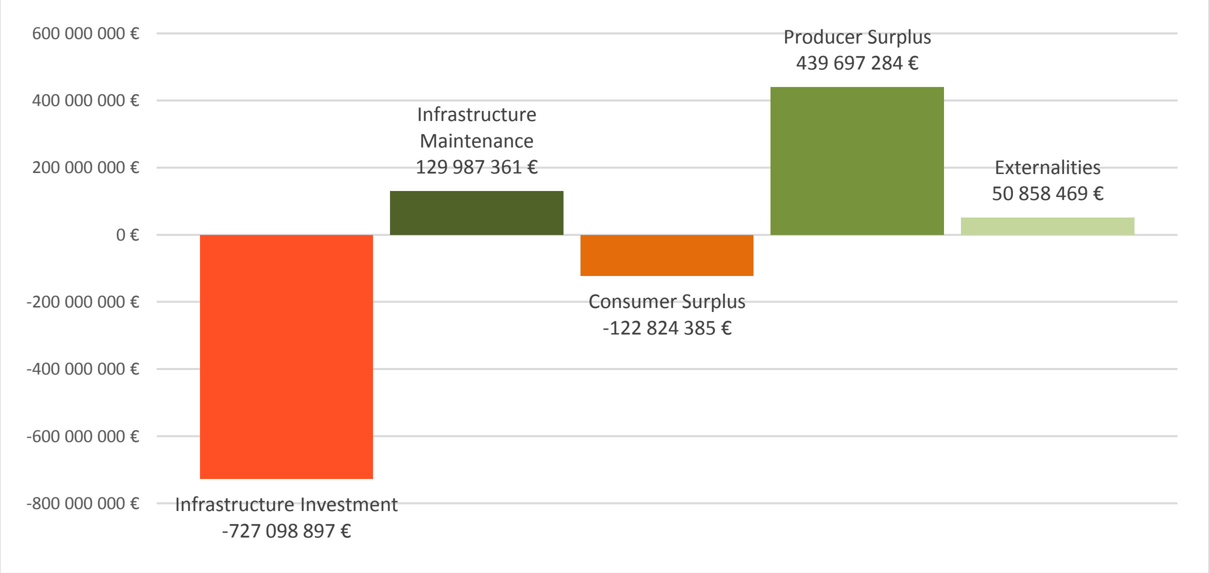

FIGURE 2. CONTRIBUTION OF CBA CATEGORIES TO THE NPV OF SCENARIO 1.

2.3.2 STAKEHOLDER EFFECTS MATRIX

Although the results presented in previous section already show the main contributions, it is useful to assign each effect to specific stakeholder, including some effects that constitute transfers and, thus, do not show up in the CBA.

As shown in Table 15, there is an overall negative effect for freight transportation users, arising from the modal transfer allowed by the increased capacity on the rail network. This negative effect is due to small reduction in average speed that is modelled between road and rail, with rail freight transportation being slightly slower.

We emphasize that we are assuming this modal transfer is solely due to demand growth that can no longer fit in the rail network in the Baseline and TEN-T investment level, but can in the C4R Scenario 1 (All). No assumptions are made regarding discrete choice, besides a small elasticity effect from unit operating costs reduction.

Despite what is stated in the preceding paragraphs, the transfer of traffic from road to rail brings a major benefit to the freight haulers, the operators.

Another major conclusion we may draw from the SE Matrix is that the infrastructure access charges (fees) raised from the increased rail traffic are far from being able to repay the increment in investment made to introduce the C4R innovations.

Finally, non-users get a non-negligible benefit from the reduction in greenhouse gas emissions.

Table 15. Stakeholder Effects (SE) Matrix of the C4R Scenario 1 (All). This matrix follows a simplified version of the RAILPAG approach.

C4R			Users	Operators	Infrastructure Manager	Non-Users	Government	**Economic Value**
			Freight	Freight	Rail			
Effects	User Service							
	Travel Time		-122 824 385 €					-122 824 385 €
	Reliability							0 €
	Operation							
	Direct	Fees		-115 858 559 €	115 858 559 €			0 €
		Vehicle Operating Costs		466 099 539 €				466 099 539 €
	Indirect	Taxes		89 456 304 €			-89 456 304 €	0 €
	Assets							
	Investment	Infrastructure			-765 367 260 €			-765 367 260 €
	Maintenance	Infrastructure			136 828 801 €			136 828 801 €
	External Effects							
	Environmental	GHG Emissions				50 858 469 €		50 858 469 €
Economic Profitability			-122 824 385 €	439 697 284 €	-512 679 901 €	50 858 469 €	-89 456 304 €	**-234 404 836 €**

2.3.3 SENSITIVITY ANALYSIS

The methodology for the Sensitivity Analysis consists in the evaluation of the effects that a positive, or negative variation on the value of each input has on the overall NPV of the considered scenarios. The adopted variation levels are: 5%, 10%, 25%, and 50%.

For this analysis, we selected the following parameters, with their respective central values:

- GDP growth: 1%
- Freight demand elasticity with GDP: 1.5
- Freight demand elasticity with Operating Costs: -0.42
- Value of Time for freight diverted from road to rail: 1.66 €/h
- C4R investment, where
    - C4R Slab track unit cost: 1000 €/m
    - C4R Switches and Crossings unit cost: 225 000 €
- Baseline and TEN-T infrastructure maintenance supplement: 5h
- C4R infrastructure maintenance supplement: 2h

The set of charts presented in Figure 3 illustrates the relative impact of each input's variation in the scenarios' NPVs.

Regarding the evolution of the NPV of the C4R scenario, in comparison to the Baseline and TEN-T:

- The impact of the variation of the GDP's annual growth is identical to the variation of the Freight demand's elasticity with the GDP. This is expected, since the Passenger demand is considered constant in the established conditions.
- Positive variations of the GDP annual growth have higher impact than negative variations, as the increased freight demand permits taking advantage of the higher capacity of the C4R trains, and their lower per unit operating costs.
- Regarding the freight demand's sensitivity to the transportation price, the response to variations in this parameter is much more subdued; this is explained by the road transportation costs being identical in both Scenarios, added to the fact that the baseline value of the Freight demand's elasticity with operating costs is quite low (-0.42).
- When considering the variations in the investments of each scenario, as expected these have a great impact in the overall NPV. The most notable is the variation of the Slab track implementation costs, which, having a higher value than other investments, has greater repercussions than a similar variation in the Baseline and TEN-T projects' investment costs.
- The variation of the Switches and Crossings' investment cost is also revealed to be preponderant, although its impact is more subdued; which is to be expected, due to its lower value.
- As expected, the variation of infrastructure maintenance times reveals that the C4R Scenario 1 (All) benefits from the extended availability of the infrastructure. It can be noted that the variation on the Baseline and TEN-T's maintenance time has a much greater impact: this is due to the higher baseline value for this variable, which will produce a greater variation range during the analysis.

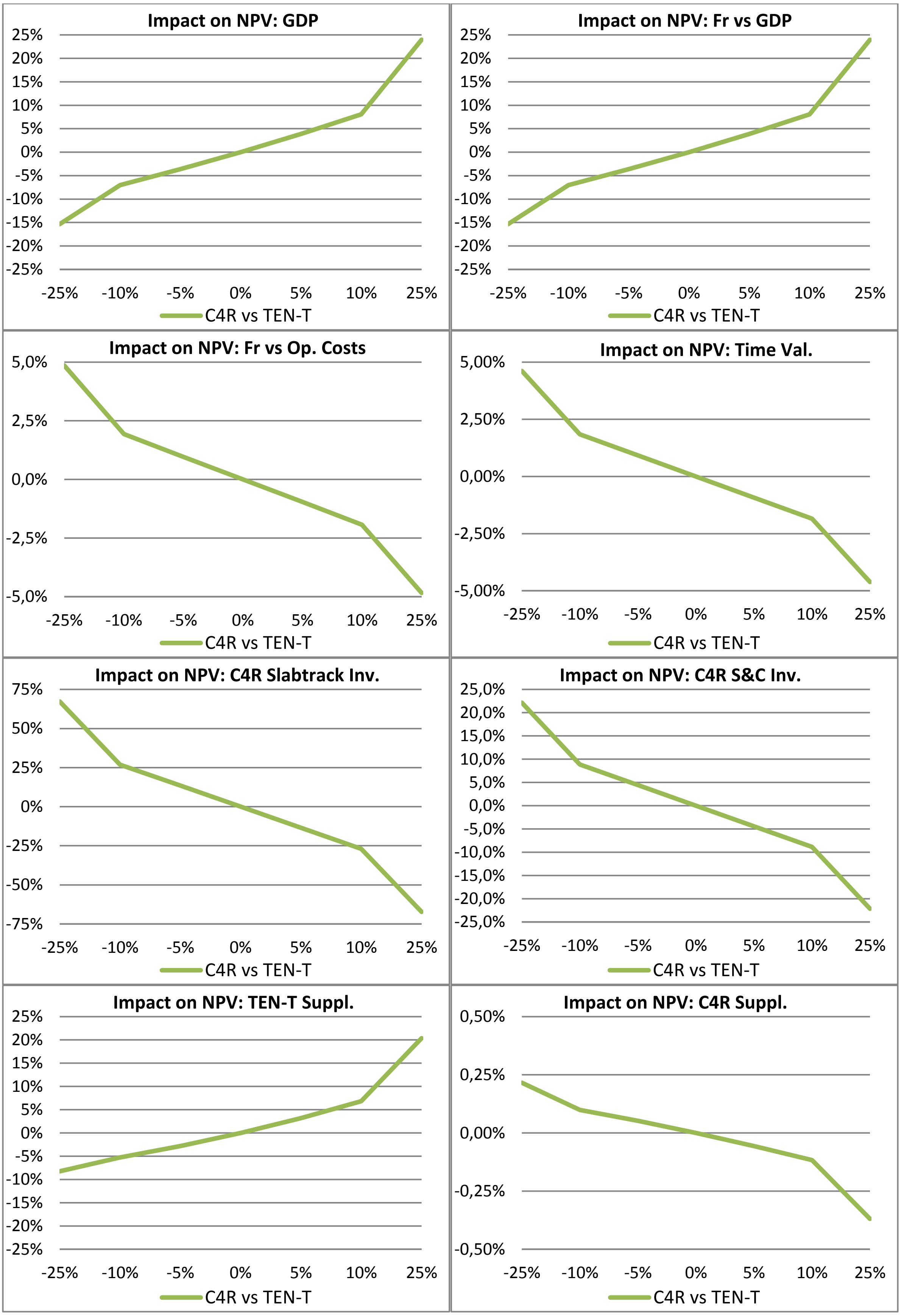

Figure 3. Effects of the Variation of each Input on the scenarios' NPVs

To summarize the impact of the selected parameters, Table 16 presents the main results.

- TABLE 16. IMPACT OF VARIABLES IN THE NPV

Variable	Relevance
C4R Slab Track Investment	a +5% variation produces a 13.45% decrease in NPV; NPV variation is symmetrical
Baseline & TEN-T Investment	a +5% var. produces a 7.58% increase in NPV; NPV variation is symmetrical
C4R S&C Investment	a +5% var. produces a 4.43% decrease in NPV; NPV variation is symmetrical
GDP, and Freight Elasticity with GDP	a +5% var. produces a 3.86% increase in NPV; positive variations have greater impact on NPV
TEN-T Maintenance Supplement	a +5% var. produces a 3.20% increase in NPV; positive variations have a greater impact on NPV
Freight Elasticity with Operation Costs	a +50% var. produces a 9.81% decrease in NPV – **not a critical variable**; NPV variation is symmetrical
Value of Time	a +50% var. produces a 9.23% increase in NPV – **not a critical variable**; NPV variation is symmetrical
C4R Maintenance Supplement	a +50% var. produces a 1.36% decrease in NPV – **not a critical variable**; positive variations have greater impact on NPV

Effect of Capacity

An additional sensitivity analysis was performed, measuring the impacts of the variation of the rail infrastructure's maximum permitted capacity occupation. Assuming a baseline where the infrastructure may be occupied to full capacity, we obtained chart in Figure 4. It's strongly asymmetrical shape, with a sharp increase in NPV if the occupation threshold is reduced suggests that this scenario is operating neat to a capacity threshold for the analysis period. In simple terms, it suggests that the rail network has "just enough" capacity to cope with traffic demand until the mid 2050's, given the assumed increases in train capacity. Should actual capacity be lower, the benefits of introducing innovations like Slab Track and new S&C will bring a greater benefit from the increased availability.

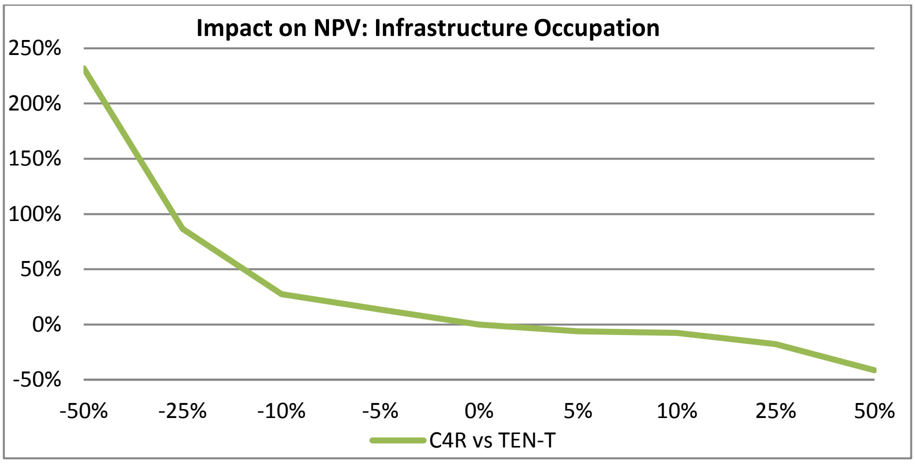

FIGURE 4. EFFECTS OF THE VARIATION OF CAPACITY OCCUPATION ON THE SCENARIOS' NPV

Based on these results, we can conclude that the infrastructure's maximum permitted occupation is also a preponderant issue in the success of the C4R project. It is interesting to notice that this intervention generates much more benefits from the reduction of the available capacity. This is not unexpected, since the benefit of creating additional capacity should become more obvious when it is in shortage.

2.3.1 PROBABILISTIC ANALYSIS

Given all the uncertainty associated with many of the parameters, it is standard procedure to conduct a probabilistic analysis on the CBA.

The probabilistic analysis follows a standard Monte Carlo method, where selected variables are turned into random values with assigned statistical distributions and a large number of results is taken. The results distribution can then be analysed and, usually, plotted into a histogram.

The probabilistic random variables selected were the same as in the sensitivity analysis above, with the respective central values:

- GDP growth: 1%
- Freight demand elasticity with GDP: 1.5
- Freight demand elasticity with Operating Costs: -0.42
- Value of Time for freight diverted from road to rail: 1.66 €/h
- C4R investment, where
  - C4R Slab track unit cost: 1000 €/m
  - C4R Switches and Crossings unit cost: 225 000 €
- Baseline and TEN-T infrastructure maintenance supplement: 5h
- C4R infrastructure maintenance supplement: 2h

Each of these variables is then assumed to have a Gaussian distribution with its central value as the mean and a standard deviation of 10% of the mean value. This straightforward approach was taken in the absence of data or assumptions on which to base a more thoughtful accounting of uncertainty.

The resulting distribution has a mean value of -223 431 266€, not dissimilar to the deterministic result, and a Standard Deviation of 173 421 661€, a little under 10% of the mean absolute value.

The histogram is shown in Figure 5, where one can verify the bell-shaped distribution resembling a Gaussian curve. The probability of a positive NPV with these assumptions is 9%, which is clearly not negligible, albeit low. This highlights the fact that one should not draw too strong conclusions from the NPV taken alone.

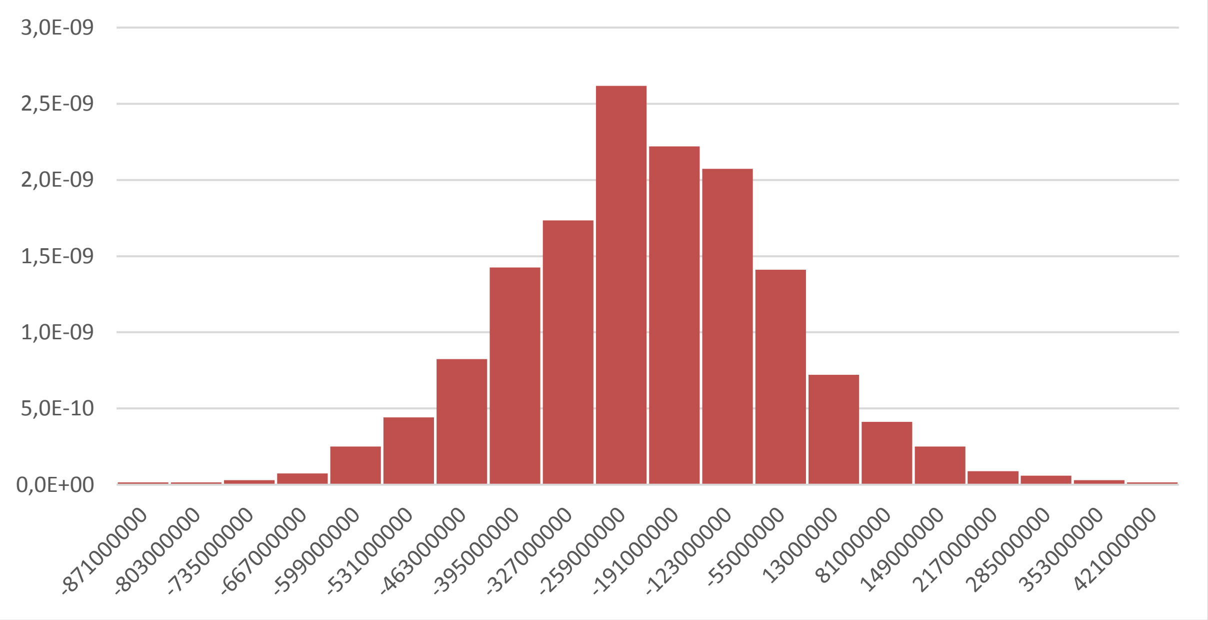

FIGURE 5. HISTOGRAM OF THE NPV FOR THE PROBABILISTIC SCENARIO 1; HORIZONTAL IS IN € AND VERTICAL AXIS IN PROBABILITY DENSITY.

2.3.2 EFFECT OF DELAYS

Some of the C4R innovations are expected to have big impacts on the reduction of unplanned unavailability and, consequentially, on the delays. For instance, some of the main aims of the new Switches and Crossings are increased reliability. The new traffic management systems developed under SP3 are also expected to mitigate the effects of unplanned unavailability by allowing a faster recovery after some event that causes delays.

Since the impacts, and indeed some specific innovations, are still poorly defined, compounded by the difficulty in finding reliable delay data, it was decided to conduct a separate analysis for the effect of delays, running Scenario 1 with assumed current delays and future reductions due to the implementation of innovation. We were able to build a model for the effect of delays with information on train punctuality in the Swedish network for 2017 provided by the partners, as presented in Table 17. We then assumed the conjugation of the innovations mentioned above would bring about an 80% reduction in overall delay minutes.

TABLE 17. REFERENCE VALUES FOR TRAIN DELAYS CALCULATION

Variable	Passenger Trains	Freight Trains
Punctual trains – arrival on schedule	73.0%	65.0%
Cancelled trains	1.0%	1.0%
Delayed trains – arrival over 1 min. after schedule	26.0%	34.0%
Average delay per delayed train per travelled 100 km	2.1 minutes	6.6 minutes
Delay reduction with the implementation of C4R innovations	80%	80%

The results presented in Table 18 show that a reduction in delays of this magnitude can have a dramatic impact on the overall results. Indeed, the single effect of delays is of the same order of magnitude as the overall NPV of Scenario 1, and it is enough to turn it from negative to positive.

It is, thus, not surprising that the sensitivity analysis on the delay reduction achieved by the innovation shows that the NPV is highly sensitive to it, as shown in Figure 6. The relative change in the NPV is always larger than the percent change introduced in the delay reduction, so it should be treated as a critical variable.

Similar conclusions may be drawn from the probabilistic analysis. Here, distributions similar to the ones used in Probabilistic Scenario 1 were considered, with the addition of a Gaussian-distributed delay reduction centred at 80% with a standard deviation of 10%.

The histogram in Figure 7 shows the wide spread of the NPV, consistent with the sensitivity analysis. Still, the distribution mentioned in the previous paragraph means it always considers a very significant reduction in delays, which accounts for a 94% probability of a positive NPV, much higher than in Scenario 1 without delays.

TABLE 18. CBA RESULTS FOR IMPLEMENTATION OF SCENARIO 1 WITH DELAYS IN THE SWEDISH SECTION OF THE SCANDINAVIAN-MEDITERRANEAN CORRIDOR. SCENARIO 1 RESULTS SHOWN FOR COMPARISON

	Net Costs	
	Scenario 1 vs ‘Baseline and TEN-T’	**Scenario 1 with Delays vs ‘Baseline and TEN-T’**
Investment	765 367 260 €	765 367 260 €
Maintenance	-136 828 801 €	-126 125 094 €
Total Financial Cost	**628 538 459 €**	**639 242 166 €**
Total Economic Cost	**597 111 536 €**	**607 280 058 €**

	Net Benefits	
	Scenario 1 vs ‘Baseline and TEN-T’	**Scenario 1 with Delays vs ‘Baseline and TEN-T’**
Consumer Surplus		
Value of Time		
Passenger Time Savings	0 €	0 €
Freight Time Savings	-122 824 385 €	-122 824 385 €
Delays	0 €	363 548 479 €
Producer Surplus		
Rail Passenger Operating Costs	0 €	0 €
Rail Freight Operating Costs	-1 389 778 994 €	-1 573 320 475 €
Road Passenger Operating Costs	0 €	0 €
Road Freight Operating Costs	1 829 476 278 €	2 183 847 977 €
Externalities		
Rail Passenger GHG Emissions	0 €	0 €
Rail Freight GHG Emissions	-1 258 931 €	-2 090 990 €
Road Passenger GHG Emissions	0 €	0 €
Road Freight GHG Emissions	52 117 400 €	62 708 109 €
Total Economic Benefits	**367 731 368 €**	**893 859 017 €**

NPV	**-229 380 168 €**	**286 578 960 €**
Internal Rate of Return		5,26%

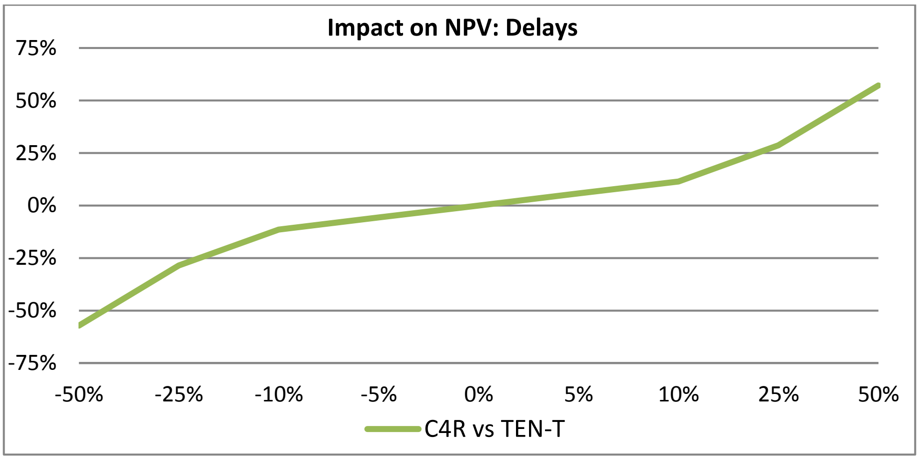

FIGURE 6. EFFECTS OF THE VARIATION OF C4R'S DELAY REDUCTION ON SCENARIO 1 WITH DELAYS NPV

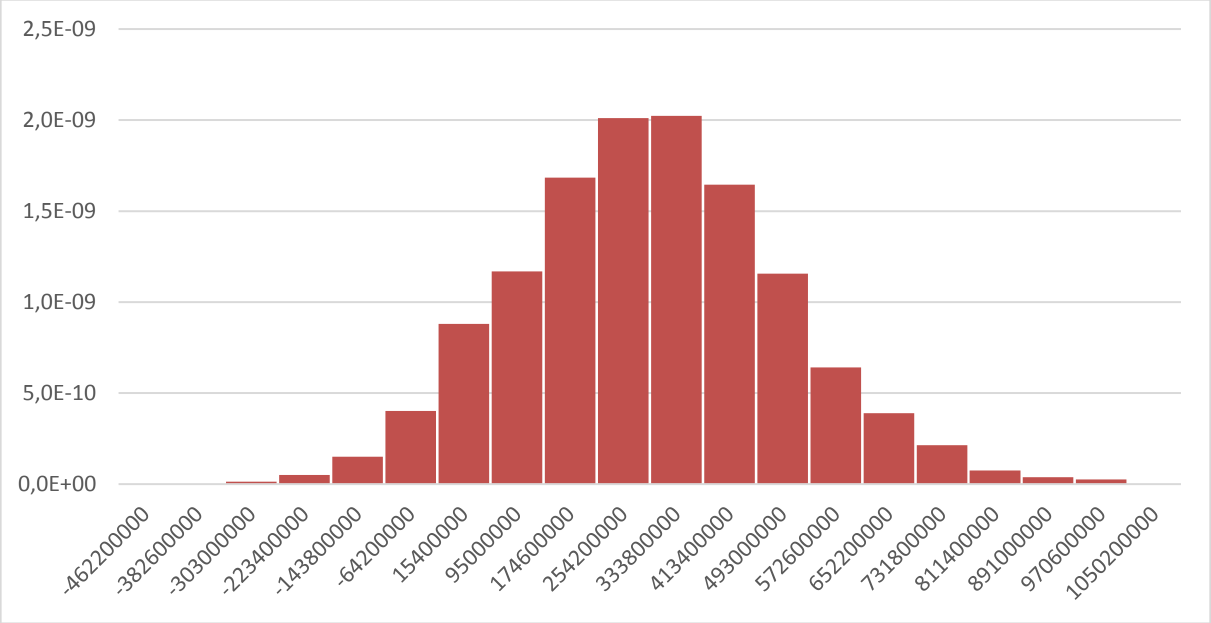

FIGURE 7. HISTOGRAM OF THE NPV FOR THE PROBABILISTIC SCENARIO 1 WITH THE ANALYSIS OF DELAYS; HORIZONTAL IS IN € AND VERTICAL AXIS IN PROBABILITY DENSITY.

2.3.3 SCENARIO 1A (ROAD TRAFFIC MIX CHANGE)

As we have discussed, the wide scope and complexity of the calculation led us to separate the analysis of some of the effects. In Scenario 1 we assumed that freight truck traffic mix would remain constant throughout the analysis period. We, thus, build Scenario 1A by assuming an evolution in the road freight vehicle traffic mix with lower cost vehicles, as described in Table 19. The results of this computation are show in Table 20.

The main effect of this change is a reduction in the average road freight unit operating cost which almost cancels out the net benefit in producer surplus arising from modal transfer. There is also a small reduction in the net benefit from the reduction in greenhouse gas emissions. Overall, this leads to a sharp reduction in the NPV of the scenario.

This highlights how much the results are dependent on the difference in operating costs working to the rail freight operators' advantage. If there the road sector closes the gap in operating costs, the economic advantage of rail transportation evaporates. Furthermore, we recall that this CBA tool has a very simple model of the model choice, based only on a demand elasticity with operating costs on the rail, mostly assuming that both modes grow linearly with GDP. It is expected that with a discrete choice model that takes into account the users' generalizes cost, there would be a much bigger reduction in the transferred traffic with the cost reductions on road freight transportation.

The effect of more dramatic changes on the road traffic mix is further explored in Scenarios 5 and 6.

TABLE 19. ROAD TRAFFIC MIX FOR SCENARIO 1A; REFERENCE ROAD FREIGH VEHICLES ARE LISTED IN TABLE 6.

Reference Vehicle	All Scenarios (From 2016 to 2029)	Scenario 1 (All) (From 2030)	Scenario 1A (From 2030)
Baseline	40%	10%	20%
After TEN-T	10%	40%	20%
Low-Cost 1	0%	0%	10%
Low Cost 2	0%	0%	5%
Future SE	0%	0%	15%
European	50%	50%	30%

TABLE 20. CBA RESULTS FOR IMPLEMENTATION OF SCENARIO 1A IN THE SWEDISH SECTION OF THE SCANDINAVIAN-MEDITERRANEAN CORRIDOR. SCENARIO 1 RESULTS SHOWN FOR COMPARISON.

	Net Costs	
	Scenario 1 (All) vs 'Baseline and TEN-T'	Scenario 1A vs 'Baseline and TEN-T'
Investment	765 367 260 €	765 367 260 €
Maintenance	-136 828 801 €	-136 828 801 €
Total Financial Cost	**628 538 459 €**	**628 538 459 €**
Total Economic Cost	**597 111 536 €**	**597 111 536 €**

	Net Benefits	
	Scenario 1 (All) vs 'Baseline and TEN-T'	Scenario 1A vs 'Baseline and TEN-T'
Consumer Surplus		
Value of Time		
Passenger Time Savings	0 €	0 €
Freight Time Savings	-122 824 385 €	-122 824 385 €
Delays	0 €	0 €
Producer Surplus		
Rail Passenger Operating Costs	0 €	0 €
Rail Freight Operating Costs	-1 389 778 994 €	-1 389 778 994 €
Road Passenger Operating Costs	0 €	0 €
Road Freight Operating Costs	1 829 476 278 €	1 609 718 922 €
Externalities		
Rail Passenger GHG Emissions	0 €	0 €
Rail Freight GHG Emissions	-1 258 931 €	-1 258 931 €
Road Passenger GHG Emissions	0 €	0 €
Road Freight GHG Emissions	52 117 400 €	48 842 263 €
Total Economic Benefits	**367 731 368 €**	**144 698 875 €**
NPV	**-229 380 168 €**	**-452 412 661 €**

2.4 ALTERNATIVE C4R SCENARIOS

The assessment methodology has been developed from the outset with the aim of comparing different scenarios in mind. These scenarios may include different combinations of the C4R innovations and may consider different geographical scopes for their implementation. In the end, this should help identify the most advantageous scenario for the introduction of the innovations.

In this study, in addition to the variation of Scenario 1, the following alternative scenarios are considered:

- Scenario 2: Partial implementation of C4R innovations, only in the most congested sections.
- Scenario 3: Implementation of Switches and Crossings' innovations, without Slab Track introduction.
- Scenario 4: Rail Positive scenario, with introduction of other rolling-stock innovations.
- Scenario 5: Road Positive scenario, with the introduction of new trucks from 2030.
- Scenario 6: Same as Scenario 5, with an additional charge on road transportation.

2.4.1 SCENARIO 2 (PARTIAL C4R)

In this scenario, we aim to assess the benefits of the partial implementation of C4R solutions in the Swedish network. As such, several implementations will be tested, were only the most congested sections will be upgraded with C4R innovations, while the remaining lines are to be renewed according to the Baseline and TEN-T interventions.

Although not every line is upgraded with C4R innovations, the same reference vehicles defined for Scenario 1 (All) in Table 3 are assumed, *i.e.* trains with up to 1000 m and 25 T/axle. This would entail an increase in track maintenance costs for non-upgraded lines, according to a factor equal to the square of the axle loads ratio. However, for the reference trains defined, there is no significant increase in the average axle loads, so no such factor needs to be applied.

For this scenario, Slab Track and new S&C were only implemented in the sections that, according to the model, have already reached their capacity limit in the starting year:

- Norrköping – Mjölby;
- Öxnered – Göteborg;
- Göteborg – Kungsbacka;
- Ängelholm - Kävlinge via Åstorp;
- Kävlinge – Lund;
- Kävlinge – Malmö.

The results for is scenario are show in Table 21.

Compared to Scenario 1, Scenario 2 involves a much more modest investment and, correspondingly, much more modest savings in maintenance costs.

However, examining the values in the producer surplus section, one finds that the penalty in operating costs reduction due, mainly, to modal transfer is not so big, providing for a significantly more favourable result than Scenario 1, in terms of NPV and IRR.

The results of this scenario somewhat reflect the indication we already had from the sensitivity analysis of Scenario 1, that there is no severe capacity shortage during the analysis period of this case study, provided new higher capacity trains are introduced.

Still, the results of this Scenario indicate that a more careful look at the introduction of Slab Track and new S&C in specific sections where they can provide some needed availability increase is not undue.

Table 21. CBA Results for implementation of Scenario 2 in the Swedish section of the Scandinavian-Mediterranean corridor. Scenario 1 results shown for comparison.

	Net Costs	
	Scenario 1 vs 'Baseline and TEN-T'	**Scenario 2 vs 'Baseline and TEN-T'**
Investment	765 367 260 €	111 524 397 €
Maintenance	-136 828 801 €	-6 431 221 €
Total Financial Cost	**628 538 459 €**	**105 093 176 €**
Total Economic Cost	**597 111 536 €**	**99 838 517 €**

	Net Benefits	
	Scenario 1 vs 'Baseline and TEN-T'	**Scenario 2 vs 'Baseline and TEN-T'**
Consumer Surplus		
Value of Time		
Passenger Time Savings	0 €	0 €
Freight Time Savings	-122 824 385 €	-94 298 436 €
Delays	0 €	0 €
Producer Surplus		
Rail Passenger Operating Costs	0 €	0 €
Rail Freight Operating Costs	-1 389 778 994 €	-1 088 509 322 €
Road Passenger Operating Costs	0 €	0 €
Road Freight Operating Costs	1 829 476 278 €	1 266 004 560 €
Externalities		
Rail Passenger GHG Emissions	0 €	0 €
Rail Freight GHG Emissions	-1 258 931 €	-13 631 €
Road Passenger GHG Emissions	0 €	0 €
Road Freight GHG Emissions	52 117 400 €	35 482 215 €
Total Economic Benefits	**367 731 368 €**	**118 665 387 €**

NPV	**-229 380 168 €**	**18 826 870 €**
Internal Rate of Return		4,35%

2.4.2 Scenario 3 (No Slab-Track)

Similarly to Scenario 2, in this scenario we will evaluate the partial implementation of C4R solutions, considering an alternative configuration where only the new Switches and Crossings are introduced as infrastructure innovations in the network.

The results in Table 22 immediately show how the investment in new S&C is almost an insignificant part of the total Scenario 1 investment, which also included Slab Track.

The conclusions one may draw from Scenario 3 are not at all dissimilar from the comments made regarding Scenario 2 in the preceding section. A much lower investment in infrastructure innovations, in this specific case, does not significantly curb the expected future growth in rail traffic. The NPV is, in this case, even more favourable.

One would be tempted to conclude, at this point, that the introduction of Slab Track is not a good solution for the Swedish portion of the Scan-Med corridor. We should, however, caution the wide scope of this analysis and, consequentially, the space it leaves for particular issues being considered in further detail.

TABLE 22. CBA RESULTS FOR IMPLEMENTATION OF SCENARIO 3 IN THE SWEDISH SECTION OF THE SCANDINAVIAN-MEDITERRANEAN CORRIDOR. SCENARIO 1 RESULTS SHOWN FOR COMPARISON.

	Net Costs	
	Scenario 1 vs 'Baseline and TEN-T'	**Scenario 3 vs 'Baseline and TEN-T'**
Investment	765 367 260 €	8 292 336 €
Maintenance	-136 828 801 €	-35 680 525 €
Total Financial Cost	**628 538 459 €**	**-27 388 189 €**
Total Economic Cost	**597 111 536 €**	**-26 018 780 €**

	Net Benefits	
	Scenario 1 vs 'Baseline and TEN-T'	**Scenario 3 vs 'Baseline and TEN-T'**
Consumer Surplus		
Value of Time		
Passenger Time Savings	0 €	0 €
Freight Time Savings	-122 824 385 €	-70 886 387 €
Delays	0 €	0 €
Producer Surplus		
Rail Passenger Operating Costs	0 €	0 €
Rail Freight Operating Costs	-1 389 778 994 €	-935 945 598 €
Road Passenger Operating Costs	0 €	0 €
Road Freight Operating Costs	1 829 476 278 €	1 074 598 020 €
Externalities		
Rail Passenger GHG Emissions	0 €	0 €
Rail Freight GHG Emissions	-1 258 931 €	508 125 €
Road Passenger GHG Emissions	0 €	0 €
Road Freight GHG Emissions	52 117 400 €	30 031 066 €
Total Economic Benefits	**367 731 368 €**	**98 305 225 €**
NPV	**-229 380 168 €**	**124 324 005 €**
Internal Rate of Return		8,88%

2.4.3 SCENARIO 4 (RAIL POSITIVE)

In this Scenario, the full implementation of C4R solutions, as in Scenario 1, is considered, along with a set of further innovations in the Rail Rolling Stock. This scenario will assume the changes discussed as follows.

Maximum speed increased from 100 to 120 km/h for ordinary freight trains will increase the energy cost for operating freight trains but at the same time reduce the travelling time and by that in some cases make it possible to use the equipment on more trips per day and by that reduce the capital costs. It will also increase capacity on day-time when freight trains have to be passed by faster passenger trains. Almost all locomotives and many wagons are already today built for a maximum speed of 120 km/h so in long term by successive replacing the existing wagons it is assumed that there will not be an additional cost for this measure.

All electric locomotives are Duo-locos means that the feeder trains can be integrated with long haul trains. The electric locos have a diesel engine which is capable to operate the train on un-electrified marshalling yards, sidings and terminal tracks. There is no need for diesel engines to shunt the trains or to handle them at inter modal terminals. The capital costs for the locomotives will be increased with 10% and at the same time the cost for feeder transports will be reduced by 50%. The cost for inter modal terminal handling will be reduced from 30 to 20 €/loading unit because of the direct access and no need for diesel shunting.

Automatic couples on all wagons will increase the cost for the wagons but at the same time decrease the costs for marshalling and shunting and in combination with duo-locos make it possible for Wagon Load to increase the market and decrease the cost per wagon. Automatic couples also make it possible to improve the length utilization by 1.1 % (for 4-axle wagons) to 1.5 % (for 2-axle wagons) and thereby handle more wagons per train. Automatic couplers also make it possible to increase the train weight and train length, in practice without limits, i.e. in US 3,000 m long trains and 10,000 tons train weight is common.

However, what we have foreseen in C4R is not a US automatic couple but a more “intelligent” automatic couple which is possible to couple and uncouple with radio control. With this kind of automatic couplers, it is also easier to implement EP-brakes and other electronic systems as monitoring systems because there will be automatic coupling of electric and radio wires also as well as air pressure.

EP-brakes on all wagons and trains will also increase the costs per wagon but at the same time reduce the maintenance cost by smoother braking and increase capacity with shorter braking distance if needed.

The future costs of automatic couplers and EP-brakes are difficult to estimate. Thera are costs for different components i.e. from US but not exact what we want adopted to the European market. Cost for prototypes is very expensive but costs for series-production in large scale of future standardized equipment may be of more reasonable price. We have assumed that the total price for a 4-axle wagon and also the maintenance cost will increase by 10 %. By calculating a 750 m long freight train with 31 Habbins-wagons the total operating cost will increase by 2 %.

The possible cost reduction because of better train performance and train monitoring system is assumed to be at least in the same order. Therefore, no additional costs have been added for these measures. The problem of these measures is not to make a calculation to show that they are profitable in long term, the main problem is to implement them and to finance a complete change in the rolling stock.

Small scale liner inter modal trains with automatic terminal handling at electrified terminals at sidings will make it possible to have liner trains with short stops at intermediate terminals along the line. With more terminals, the average feeder distance to the customers will decrease and the market will widen down to 200 km for inter modal in bets cases.

A calculation of an automatic small-scale liner terminal with the AMCCT-system in WP2.3 showed that it is possible to reduce the transferring cost of a loading unit (LU) from 30 €/LU to 10 €/LU. More terminals along the line will reduce the average feeder distance from 50 to 30 km one way.

Considering this discussion, we established the reference freight trains for Scenario 4 as listed in Table 23.

For these system conditions, the resulting values are presented in Table 24.

Here we witness a leapfrog in terms of NPV relative to any other scenario. This is indeed the most favourable of all the scenarios considered in this case study. A quick inspection of Table 24 reveals that a significant portion of the advantage of this scenario comes from time savings, reflecting the increase in freight train speed that is assumed for this scenario. The remaining fields have comparable values to Scenario 1.

TABLE 23. REFERENCE FREIGHT TRAINS FOR THE SCENARIO 4

Characteristics	Train Load	Wagon Load	IM Container	IM Trailer	WL Feeder	IM Liner
Length (m)	997	997	998	981	986	599
Tare Weight (T)	877.6	828	685.7	579	729.2	476.4
Axle Load (T/axle)	17.9	16.4	16.1	16.3	13.6	16.1
Cargo Capacity (T)	2024	1942	1447	2053	1925	960
Average Load Factor	50%	55%	50%	53%	45%	60%
Average Load (T)	1012	1068	723	1088	866	576
Average Gross Weight (T)	1890	1896	1409	1667	1595	1052
Operating Costs [€/(T·km)]	0.0128	0.0136	0.0177	0.0124	0.0129	0.0175
Tax [€/(T·km)]	0.0046	0.0027	0.0050	0.0037	0.0045	0.0045
Terminal Costs [€/(T·km)]		0.0051	0.0076	0.0083		0.0073
Tax [€/(T·km)]		0.0021	0.0013	0.0014		0.0013
GHG Emissions [kg/(T·km)]	0.0019	0.0021	0.0025	0.0017	0.0017	0.0023

TABLE 24. CBA RESULTS FOR IMPLEMENTATION OF SCENARIO 4 IN THE SWEDISH SECTION OF THE SCANDINAVIAN-MEDITERRANEAN CORRIDOR. SCENARIO 1 RESULTS SHOWN FOR COMPARISON.

	Net Costs	
	Scenario 1 vs ‘Baseline and TEN-T’	**Scenario 4 vs ‘Baseline and TEN-T’**
Investment	765 367 260 €	765 367 260 €
Maintenance	-136 828 801 €	-134 766 734 €
Total Financial Cost	**628 538 459 €**	**630 600 526 €**
Total Economic Cost	**597 111 536 €**	**599 070 500 €**

	Net Benefits	
	Scenario 1 vs ‘Baseline and TEN-T’	**Scenario 4 vs ‘Baseline and TEN-T’**
Consumer Surplus		
Value of Time		
Passenger Time Savings	0 €	0 €
Freight Time Savings	-122 824 385 €	1 378 705 285 €
Delays	0 €	0 €
Producer Surplus		
Rail Passenger Operating Costs	0 €	0 €
Rail Freight Operating Costs	-1 389 778 994 €	-1 455 498 345 €
Road Passenger Operating Costs	0 €	0 €
Road Freight Operating Costs	1 829 476 278 €	1 858 828 163 €
Externalities		
Rail Passenger GHG Emissions	0 €	0 €
Rail Freight GHG Emissions	-1 258 931 €	-9 831 782 €
Road Passenger GHG Emissions	0 €	0 €
Road Freight GHG Emissions	52 117 400 €	52 897 944 €
Total Economic Benefits	**367 731 368 €**	**1 825 101 265 €**

NPV	**-229 380 168 €**	**1 226 030 765 €**
Internal Rate of Return		9,74%

2.4.4 SCENARIOS 5 & 6 (ROAD POSITIVE)

In Scenario 5, we assume an evolution in the road traffic mix from the year 2030 onwards, with the introduction of truck innovations according to the actual development and proposals in Sweden and the development of autonomous operated trucks in the following ways:

- Maximum gross weight for trucks in Sweden will be increased from 64 tonnes 2016 to 74 tonnes from 2020.
- Maximum length for trucks are increased from 25,25 m 2016 to 34 m 2030 allowing one truck to haul two trailers or two 45 feet containers
- Autonomous trucks with no driver will be implemented from 2030.

Sweden has since long time ago very long and heavy. In the beginning of 1990s the maximum weight was increased from 40 to 60 tonnes. The possible payload then increased from approx. 26 to 40 tonnes with a reduction in transport cost by approx. 25 %. In 2016 the maximum gross weight was increased from 60 to 64 tonnes and the payload from 40 to approx. 43.5 tonnes. This means that the cost per tonnes km will decrease with 6 % but is not fully implemented yet.

In Sweden there has been experiment with trucks up to 90 tonnes gross weight and 34 m length and in some cases they have been allowed for special transports. An evaluation has been made of different truck types by Lund University and there have been political proposals to implement 74 tonnes gross weight and 34 m truck lengths, not yet accepted by the parliament. At the same time there are proposals to introduce distance based road charges for trucks which are not even decided yet.

If 74 tonnes trucks will be implemented the cost per tonnes-km will decrease by 14 % compared with 60 tonnes trucks which is the most common today and by 8 % compared by 64 tonnes trucks. If 34 m long trucks will be introduced the cost per trailer or 45 feet container will decrease with 42 % compared with a 18 m truck with one trailer.

Autonomous trucks with no driver are technically possible already today, but it will take time to implement the infrastructure and legal conditions for that. There will be some additional cost for this with the IT-systems in the trucks but at the same time the potential for savings in personal costs are considerable if it is possible to skip the driver from the cab most of the way. It will be comparable with a low-cost truck today, there the cost for the driver can be only 10 % of an ordinary truck.

A low cost truck, with 10 % of the normal driver cost, has a cost which is approx. 35 % lower than an ordinary truck. That is what we assume for an autonomous truck because we think there must be a driver at the origin and destination. Then there is an additional cost for the IT-system but there are also savings in optimized driving and platooning, so we assume a net reduction of the tonnes-km cost by 35 %.

In the evaluation of different truck types made by Lund University there was also one alternative where the implementation of longer and heavier trucks was completed by distance based charges for trucks. An alternative with charge at 0.16 €/truck-km was also the most socio-economic profitable alternative. Therefore, it could be interesting to include this in the truck-positive scenario. This constitutes Scenario 6.

The Road Reference Vehicles and Traffic Mix considered for Scenario s 5 are presented in Table 25. Scenario & uses the same figures, except for the addition of a 0.16 €/truck-km charge that causes a slight increase in the operating costs.

TABLE 25. REFERENCE ROAD VEHICLES AND ROAD TRAFFIC MIX FOR SCENARIO 5

	Baseline	After TEN-T	Autonomous	Future SE	Future SE	European
Characteristics						
Maximum Load (T)	40	43.5	43.5	50	50	26
Average Load Factor	60%	60%	60%	60%	60%	60%
Average Load (T/vehicle)	24	26.1	26.1	30	30	15.6
Operating Costs [€/(T·km)]	0.0575	0.0536	0.0379	0.0487	0.0487	0.0814
Tax [€/(T·km)]	0.0121	0.0115	0.0069	0.0107	0.0107	0.0160
GHG Emissions [kg/(T·km)]	0.0320	0.0310	0.0320	0.0310	0.0290	0.0420
Traffic Mix						
	0%	26%	26%	21%	21%	6%

TABLE 26. CBA RESULTS FOR IMPLEMENTATION OF SCENARIOS 5 AND 6 IN THE SWEDISH SECTION OF THE SCANDINAVIAN-MEDITERRANEAN CORRIDOR. SCENARIO 1 RESULTS SHOWN FOR COMPARISON.

	Net Costs		
	Scenario 1 vs 'Baseline and TEN-T'	**Scenario 5 vs 'Baseline and TEN-T'**	**Scenario 6 vs 'Baseline and TEN-T'**
Investment	765 367 260 €	765 367 260 €	765 367 260 €
Maintenance	-136 828 801 €	-136 828 801 €	-136 828 801 €
Total Financial Cost	**628 538 459 €**	**628 538 459 €**	**628 538 459 €**
Total Economic Cost	**597 111 536 €**	**597 111 536 €**	**597 111 536 €**

	Net Benefits		
	Scenario 1 (All) vs Baseline and TEN-T	**Scenario 5 vs Baseline and TEN-T**	**Scenario 6 vs Baseline and TEN-T**
Consumer Surplus			
Value of Time			
Passenger Time Savings	0 €	0 €	0 €
Freight Time Savings	-122 824 385 €	-122 824 385 €	-122 824 385 €
Delays	0 €	0 €	0 €
Producer Surplus			
Rail Passenger Operating Costs	0 €	0 €	0 €
Rail Freight Operating Costs	-1 389 778 994 €	-1 389 778 994 €	-1 389 778 994 €
Road Passenger Operating Costs	0 €	0 €	0 €
Road Freight Operating Costs	1 829 476 278 €	1 327 314 743 €	1 477 768 055 €
Externalities			
Rail Passenger GHG Emissions	0 €	0 €	0 €
Rail Freight GHG Emissions	-1 258 931 €	-1 258 931 €	-1 258 931 €
Road Passenger GHG Emissions	0 €	0 €	0 €
Road Freight GHG Emissions	52 117 400 €	44 855 140 €	44 855 140 €
Total Economic Benefits	**367 731 368 €**	**-141 692 428 €**	**8 760 885 €**
NPV	**-229 380 168 €**	**-738 803 964 €**	**-588 350 652 €**

The results shown in Table 26 show that this scenario, with or without the additional fee would nothing short of a disaster for the rail transportation, with assumptions we have made and discussed as to it’s foreseeable evolution.

Focusing on the producer surplus section, one realizes that the difference in operating costs that worked to the advantage of the rail sector in all other scenarios, has simply vanished, taking with it the main benefit that balanced the results in other scenarios.

The additional charge modelled in Scenario 6 is able to restore a very slim advantage in operating costs for the rail, but still not enough to even compensate the losses in value of time.

The results of these scenarios highlight the importance of considering the expected evolution of other modes of transportation, namely, the road, when attempting to plane for the next few decades of railway transportation innovations.

3 Case Study 2: Montpellier-Perpignan section of the Mediterranean Corridor

3.1 BACKGROUND

Here we present the summary of another analysis performed within the framework of a demonstration activity (included in Deliverable 5.5.6.). This case study models in detail a shorter section, as part of the Mediterranean TEN-T Corridor, just north of the French-Spanish border between Montpellier and Perpignan. This section under analysis here is considered the critical section in terms of capacity of the overall Perpignan – Luxembourg route, an important axis in the French rail network. As in the previous case study, the analysis is focused on freight transportation.

Within the demonstration it was possible to assemble and model very detailed data on both traffic and infrastructure characteristics in this section, in order to build a realistic business case to assess the possible impact of C4R innovations. Many of the assumptions and inputs for the case study were discussed at length, with a final agreement reached during a Workshop Meeting of partners from SP5 and SP2 in Paris on April 12 and 13, 2017. All the detailed assumptions and results for this case study can be looked up in the specific Annex (working document) included within Deliverable 5.5.6.

3.2 CORRIDOR DESCRIPTION

The Rail Corridor under analysis extends from Montpellier to Perpignan. This includes a section along the Tarascon to Narbonne line between Montpellier and Narbonne, where the Narbonne to Port-Bou line begins. Of the latter, we include the portion from Narbonne to Perpignan. The corridor section is shown on the map in Figure 8. The corridor is segmented as shown in Table 27 into section with uniform features with traffic.

This stretch of rail runs roughly parallel to the A9 AutoRoute between Montpellier and Perpignan, which makes this the main road alternative, as shown on the map in Figure 9. This is a section of motorway 148 km length. We assume that most traffic does not have Montpellier or Perpignan as their origin or destination and, for this reason, we only consider the A9 route itself and not the connections to the cities themselves. Since some of the actual traffic will have origin and destination within the corridor, this means we will slightly underestimate average distances and travel times for road traffic.

The discussions during the Paris Workshop allowed us to establish the rail section between Montpellier and Narbonne as a bottleneck for the entire Perpignan – Luxembourg corridor, meaning that future traffic growth would be limited by the capacity in this section. Obtaining a precise figure for the current capacity occupation and potential number of additional trains that could still be accommodated would be extremely difficult. For these reasons, and for the purposes of this Case Study, we treated the section between Montpellier and Narbonne as being currently operating at 100% capacity, so no additional trains are allowed to run unless change in the conditions of the infrastructure are made.

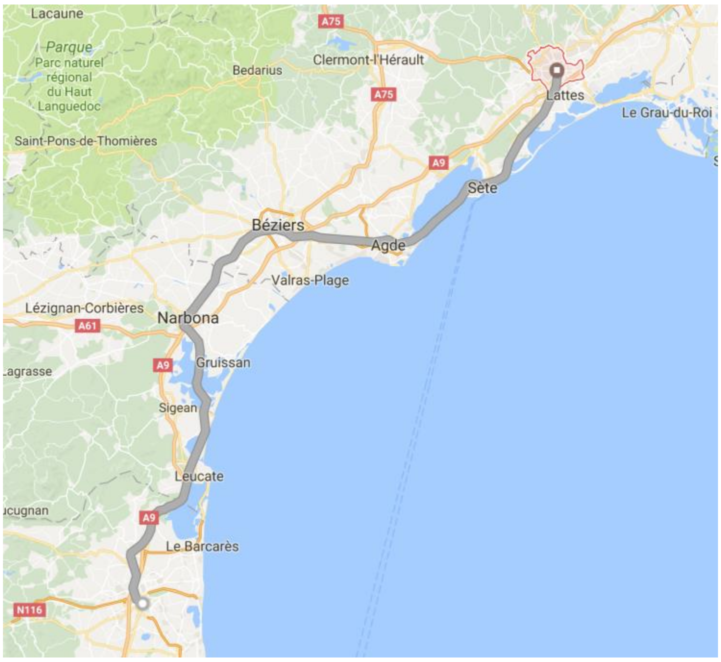

Figure 8. Map of the Rail corridor under analysis, connecting Montpellier to Perpignan.

Table 27. Rail Corridor Sections

Section	Length (km)	No. of Tracks
Montpelier (km 76,9) - Séte (km 104,5)	27,6	2
Séte (km 104,5/475,9) - Béziers (km 431,6)	44,3	2
Béziers (km 431,6) – Narbonne (Bif. Port-Bou) (km 404,7)	27,9	2
Narbonne (Bif. Port-Bou) (km 404,7) - Perpignan (km 467,5)	62,8	2

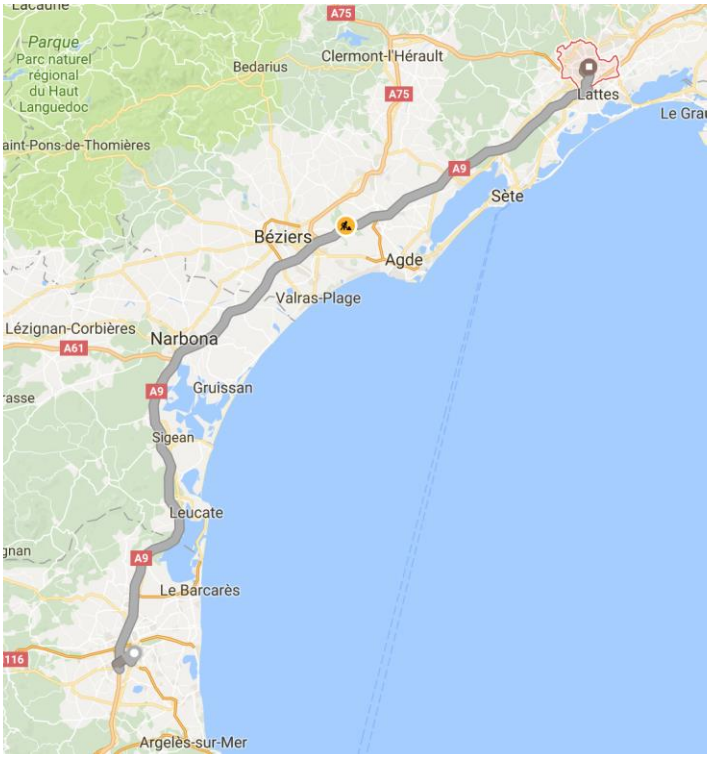

Figure 9. Map of the Road corridor connecting Montpellier to Perpignan through the A9 AutoRoute.

3.3 INPUT DATA FOR SCENARIO 1

3.3.1 REFERENCE VALUES

Like in the Sweden case study, the CBA parameters were set as:

- 40-year time horizon with 2016 as "year 1";
- Financial and social discount rates of 4%;
- Shadow price conversion factor of 0,95.

The time horizon, discount rates and conversion factor are within the typical bounds set by the EC Guidelines.

3.3.2 INVESTMENT SCENARIO

For the particular section in analysis, there are no planned projects connected with the TEN-T initiative. We thus define, for each C4R Scenario, two Investment Levels over the Baseline:

- the **Baseline** or "business as usual", where only routine investments to maintain current conditions are considered, namely track and switch renewals;
- **Investment Level 1** includes the required interventions to allow for the operation of trains up to 1000 m in length;
- **Investment Level 2** includes the required interventions to allow for the operations of trains up to 1500 m in length.

The infrastructure currently allows for the running of trains up to 850 m long, limited by the sidings at Agdes and Port-la-Nouvelle. These sections have been last renewed in 2015 and the next renewal is not expected to take place until 2035, assuming a 20 year renewal cycle for track and switches and crossings.

Strictly speaking, the lengthening of these sidings is the only required investment in the infrastructure to allow for the longer trains. We assume that, were such investment to be made, it would always be designed to allow for the longer 1500 m trains, regardless of immediate plans to introduce them or not.

The longer freight trains envisaged and already planned to run on this corridor can be obtained either through the straightforward addition of more wagons or through the coupling of two of the existing trains. In either case, this requires more or less modest investment in the rolling stock braking systems, with the introduction of Electro-Pneumatic (EP) brakes and the End-of-Train device to allow for more efficient braking and faster brake release, and command and control systems to allow for the coupled trains. We assume this capital cost to be diluted into the assumed operating costs.

For Investment Level 2 we shall also consider the replacement of the current track system with a Slab Track at the time of the next renewal along with innovative Switches and Crossings. Both these technologies are being developed as part of C4R SP1. Their introduction is expected to have as main effects the reduction of required daily down time for maintenance and a decrease in track maintenance costs corresponding to the cost of tamping, no longer required for a ballast-less track.

To summarize, the investments and unit costs for the Paris Workshop Scenario are as follows, for the **Baseline**:

- Track renewal performed in 2035 at a cos of 700000 €/km of single track;
- Switch and crossing renewal performed in 2035 at a cost of 150000 €/switch.

In **Investment Level 1**, the following is additionally considered:

- Siding extension at Agdes and Port-la-Nouvelle at a cost of 2 000 000 €/siding for a total of 4 sidings being performed in 2019.

Investment Level 2, is built incrementally from Investment Level 1 by considering that:

- A slab track is constructed between 2035 and 2036 at a cost of 1 000 000 €/km of single track, eliminating the need for the track renewal in 2035.

3.3.3 INFRASTRUCTURE DATA

Travel times and corresponding average speeds for passenger and freight trains were derived from scheduling data. While there is some variation, especially in freight trains, it was possible to obtain approximate average values. In the case of freight trains, however, the figures used only account for the time it takes to traverse this section, not including marshalling or shunting nor the prolonged stops to be overtaken by faster trains that are sometimes included in the schedules. Nevertheless, this allows for the direct comparison with the figures used for the road, that also don't include loading and unloading times nor access to cities, as mentioned in Section 3.2.

As mentioned in the previous section, the implementation of Slab Track is expected to positively affect maintenance costs and track down time for maintenance. We thus assumed that the implementation of slab track eliminates tamping costs, resulting in a saving of 8000 €/(year·track) from a baseline cost of 14000 €/(year·track), as discussed and agreed in the Paris Workshop. It is also assumed that Slab Track would lead to a reduction of the supplement for maintenance from the current daily 5 h/track to 2 h/track.

3.3.4 TRAFFIC SCENARIO

Traffic demand evolution was modelled using the existing traffic in number of vehicles in year 0, 2016, and a set of elasticities, which is equivalent to modelling a linear relationship between a set of variables and traffic demand. The current number of trains in the section was counted from the schedules that were made available for this case study.

The baseline freight traffic forecast is based on the following parameters:

- Annual GDP Growth: 1%;
- Freight Demand Elasticity with GDP: 1.5;
- Freight Demand Elasticity with Operating Costs: -0.42.

Since passenger traffic is kept constant throughout the analysis period, its elasticities are set at 0.

We also assume that the section under analysis remains the bottleneck on the overall corridor despite the capacity increases.

The computation of the actual rail traffic takes into account demand growth as well as capacity availability. In this scenario is assumed that, if not further capacity is available on the rail network, the exceeding traffic demand is transferred to the road. This demand transferred due to lack of capacity then returns to the rail if and when surplus capacity becomes available.

3.3.5 REFERENCE VEHICLES

The set of freight reference trains to be used in the model of the Montpellier – Narbonne section was discussed at length at the Paris Workshop of April 12-13.

The freight traffic was divided into five market segments: Train Load, Wagon Load, Container, Trailer and Trailer with Horizontal Loading. For each of these segments a baseline reference train that aims to represent the existing traffic in this section was defined.

Future trains were also defined for Investment Level 1, with lengths up to 1000 m, and for Investment Level 2, with lengths up to 1500 m.

Operating Costs were taken simply as 7 €/km for a locomotive and 0,3 €/km for a freight wagon, also as agreed during the Paris Workshop. These values were provided by the SP2 costs model. This is meant to include capital costs, but not access charges or special taxes on energy. The main characteristics of the considered reference trains are listed in Table 28 to Table 30.

A reference road freight vehicle also needed to be established. In this case, we consider a 40 T truck with a Maximum Load of 26 T and an average Load Factor of 60%. The operating costs are set at 0,6 €/(vehicle·km).

TABLE 28. BASELINE REFERENCE FREIGHT TRAINS FOR SCENARIO 1

	Train Load	**Wagon Load**	**Container**	**Trailer**	**Trailer Horizontal Loading**
Number of Locomotives	1	1	1	1	1
Number of Wagons	25	25	26	21	23
Length (m)	340,5	370	727,2	738,2	820,4
Tare (T)	515	515	888,2	810,3	1062,9
Maximum Load (T)	1825	1825	2704	1386	1518
Load Factor	60%	30%	55%	77%	96%
Load (T)	1095	548	1487	1067	1457
Gross Weight (T)	1610	1063	2375	1878	2520

TABLE 29. INVESTMENT LEVEL 1 REFERENCE FREIGHT TRAINS FOR SCENARIO 1

	Train Load	**Wagon Load**	**Container**	**Trailer**	**Trailer Horizontal Loading**
Number of Locomotives	2	1	1	1	1
Number of Wagons	75	70	36	28	28
Length (m)	998,5	1000	999,2	977,6	994,4
Tare (T)	1455	1280	1195,2	1050,4	1274,4
Maximum Load (T)	5475	5110	3744	1848	1848
Load Factor	60%	30%	55%	77%	96%
Load (T)	3285	1533	2059	1423	1774
Gross Weight (T)	4740	2813	3254	2473	3048

TABLE 30. INVESTMENT LEVEL 2 REFERENCE FREIGHT TRAINS FOR SCENARIO 1

	Train Load	**Wagon Load**	**Container**	**Trailer**	**Trailer Horizontal Loading**
Number of Locomotives	2	1	2	1	2
Number of Wagons	114	25	53	42	41
Length (m)	1493,8	370	1481,6	1456,4	1466,8
Tare (T)	2118	515	1807,1	1530,6	1914,3
Maximum Load (T)	8322	1825	5512	2772	2706
Load Factor	60%	30%	55%	77%	96%
Load (T)	4993	548	3032	2134	2598
Gross Weight (T)	7111	1063	4839	3665	4512

3.4 RESULTS FOR SCENARIO 1

The CBA results presented in Table 31 display, at first glance, a positive NPV and generous IRR values for both investment levels. The NPV for both investment levels are, actually, of the same order of magnitude, despite the much more ambitious investments included in Investment Level 2. This explains why the IRR is much higher in Investment Level 1.

Looking at the different categories in the CBA, the mechanisms at work are not qualitatively different from the ones observed in the Sweden case study. The largest benefits are still generated in the Producer Surplus category due to modal transfer from road to rail. This effect mostly arises from released capacity in the rail corridor after the introduction of longer trains and, in the case of Investment Level 2, infrastructure innovations that increase availability by up to 3h/day.

Still, it is noteworthy that a much higher infrastructure investment in Investment Level 2 leads to a similar, indeed slightly lower NPV, even combined with further innovation on the operation that further increase train capacity and reduce unit operating costs.

TABLE 31. CBA RESULTS FOR MONTPELLIER-PERPIGNAN SCENARIO 1 INVESTMENT LEVELS 1 AND 2.

	Net Costs	
	Scenario 1 Inv. Level 1 vs Baseline	**Scenario 1 Inv. Level 2 vs Baseline**
Investment	7 111 971 €	62 874 880 €
Maintenance	0 €	-16 136 288 €
Total Financial Cost	**7 111 971 €**	**46 738 592 €**
Total Economic Cost	**6 756 372 €**	**44 401 663 €**

	Net Benefits	
	Scenario 1 (All) vs Baseline and TEN-T	**Scenario 2 vs Baseline and TEN-T**
Consumer Surplus		
Value of Time		
Passenger Time Savings	0 €	0 €
Freight Time Savings	-9 829 491 €	-26 297 551 €
Delays	0 €	0 €
Producer Surplus		
Rail Passenger Operating Costs	0 €	0 €
Rail Freight Operating Costs	-97 197 635 €	-218 113 901 €
Road Passenger Operating Costs	0 €	0 €
Road Freight Operating Costs	237 359 352 €	393 835 364 €
Externalities		
Rail Passenger GHG Emissions	0 €	0 €
Rail Freight GHG Emissions	26 267 €	-77 398 €
Road Passenger GHG Emissions	0 €	0 €
Road Freight GHG Emissions	12 527 827 €	21 223 681 €
Total Economic Benefits	**142 886 319 €**	**170 570 194 €**

NPV	**136 129 947 €**	**126 168 531 €**
Internal Rate of Return	43,94%	23,03%

3.5 RESULTS FOR SCENARIO 3 (NO SLAB TRACK)

In order to isolate the effect of the upgrade to Slab Track, Scenario 2 was constructed, where this investment is not considered nor are its effects on the availability and maintenance costs.

The bottom lines in Table 32 show a slightly smaller NPV but a higher IRR, which is explained by a sharper decrease in infrastructure investment compared to the reduction in benefits relative to Scenario 1.

Differently from the Sweden case study, this scenario shows that the high investment costs in slab track introduction may prove to be economically beneficial in capacity constrained section such as the Montpellier-Perpignan section, provided they deliver a significant increase in availability with the corresponding increase in capacity. However, it is important to recall that the increased availability modelled in this case study may not be easy to achieve, namely, if it is only obtained in this specific section. On the other hand, introducing slab track in adjacent sections as well would increase investment. Despite these caveats, this results further shows how beneficial it can be to obtain capacity increases in bottlenecks such as the Montpellier-Perpignan section.

TABLE 32. CBA RESULTS FOR MONTPELLIER-PERPIGNAN SCENARIO 3 INVESTMENT LEVEL 2 (NO SLAB TRACK), WITH SCENARIO 1 INVESTMENT LEVEL 2 PRESENTED FOR REFERENCE.

	Net Costs	
	Scenario 1 Inv. Level 2 vs Baseline	**Scenario 3 Inv. Level 2 vs Baseline**
Investment	62 874 880 €	10 922 345 €
Maintenance	-16 136 288 €	0 €
Total Financial Cost	**46 738 592 €**	**10 922 345 €**
Total Economic Cost	**44 401 663 €**	**10 376 228 €**

	Net Benefits	
	Scenario 1 (All) vs Baseline and TEN-T	**Scenario 2 vs Baseline and TEN-T**
Consumer Surplus		
Value of Time		
Passenger Time Savings	0 €	0 €
Freight Time Savings	-26 297 551 €	-20 490 110 €
Delays	0 €	0 €
Producer Surplus		
Rail Passenger Operating Costs	0 €	0 €
Rail Freight Operating Costs	-218 113 901 €	-176 220 598 €
Road Passenger Operating Costs	0 €	0 €
Road Freight Operating Costs	393 835 364 €	291 540 999 €
Externalities		
Rail Passenger GHG Emissions	0 €	0 €
Rail Freight GHG Emissions	-77 398 €	49 983 €
Road Passenger GHG Emissions	0 €	0 €
Road Freight GHG Emissions	21 223 681 €	15 824 584 €
Total Economic Benefits	**170 570 194 €**	**110 704 858 €**

NPV	**126 168 531 €**	**100 328 629 €**
Internal Rate of Return	23,03%	25,88%

3.6 RESULTS FOR SCENARIO 5 (ROAD POSITIVE)

Given the high rate if innovation in road transportation, the main competitor of rail freight transportation, it is important to check what effect these innovations may have on the economic outcomes of the investments being considered for the rail.

We used the Road Positive scenario of the Swedish case study as a benchmark to construct a similar scenario for the Mediterranean corridor section here presented. In practical terms, this means we are simply assuming a 28% decrease in road operating costs by 2030. Differently from Sweden, it is not expected that there will be increases in length and gross weight of freight trucks in France for the foreseeable future.

As expected, the reduction in road unit operating costs sharply cuts the benefits arising from modal transfer. However, this benefit is not completely eliminated since rail unit operating costs are still significantly lower than road's.

The reduction in the producer surplus benefit is the responsible for the very sharp decline in in NPV and IRR, although, in this case, it remains positive. The difference between these results and the ones from the Sweden case study further highlight how specific the analysis of capacity constrained sections is and how they have the biggest potential for making investment in advanced solutions for the railway profitable.

TABLE 33. CBA RESULTS FOR MONTPELLIER-PERPIGNAN SCENARIO 5 (ROAD POSITIVE) INVESTMENT LEVELS 1 AND 2..

	Net Costs	
	Scenario 5 Inv. Level 1 vs Baseline	**Scenario 5 Inv. Level 2 vs Baseline**
Investment	7 111 971 €	62 874 880 €
Maintenance	0 €	-16 136 288 €
Total Financial Cost	**7 111 971 €**	**46 738 592 €**
Total Economic Cost	**6 756 372 €**	**44 401 663 €**

	Net Benefits	
	Scenario 1 (All) vs Baseline	**Scenario 2 vs Baseline and TEN-T**
Consumer Surplus		
Value of Time		
Passenger Time Savings	0 €	0 €
Freight Time Savings	-6 346 593 €	-23 194 169 €
Delays	0 €	0 €
Producer Surplus		
Rail Passenger Operating Costs	0 €	0 €
Rail Freight Operating Costs	-64 293 286 €	-187 944 664 €
Road Passenger Operating Costs	0 €	0 €
Road Freight Operating Costs	113 044 321 €	257 886 590 €
Externalities		
Rail Passenger GHG Emissions	0 €	0 €
Rail Freight GHG Emissions	15 €	-103 651 €
Road Passenger GHG Emissions	0 €	0 €
Road Freight GHG Emissions	1 863 516 €	12 238 578 €
Total Economic Benefits	**47 164 601 €**	**58 882 684 €**
NPV	**40 408 229 €**	**14 481 022 €**
Internal Rate of Return	14,78%	6,25%

4 Ranking of Scenarios and Discussion

4.1 RANKING OF SCENARIOS FOR SWEDEN CASE STUDY

To sum up the discussion in the Sweden case study, we recall the scenarios that were considered:

- Scenario 1: All innovations in all sections
- Scenario 2: Partial implementation of C4R innovations, only in the most congested sections.
- Scenario 3: Implementation of Switches and Crossings' innovations, without Slab Track introduction.
- Scenario 4: Rail Positive scenario, with introduction of other rolling-stock innovations.
- Scenario 5: Road Positive scenario, with the introduction of new trucks from 2030.
- Scenario 6: Same as Scenario 5, with an additional charge on road transportation.

The ranking of scenarios presented in Figure 10 and Figure 11, for the deterministic and probabilistic cases, respectively, give us a good starting point for a discussion of the overall mechanisms at work in this scenario.

The first point to note is that the three lowest ranking scenarios (Scen. 6, 5 and 1A) are the ones that, in different degrees, assume some kind of evolution in road transportation leading to lower average operating costs. Even if they remain slightly higher than on the rail, as in Scenario 1A, this still represents a challenge for the rail freight transportation business.

The significant difference in NPV between scenarios 5 and 6 shows the effect that policies, namely the introduction of specific charges for the road sector can be beneficial from the standpoint of return on investments in the railways.

In the analysis of Scenario 1 (All) results we have commented that the modal transfer or freight traffic from road to rail making use of the increased capacity. However, it was not clear it was from the increase in train capacity or if there was an increase in number of trains allowed by the reduction in planned unavailability. The comparison of Scenarios 1 and 2 (Partial Slab Track) suggests that it is only the former and there is no big advantage in the implementation of Slab Track. This goes in same direction as the conclusion from the sensitivity analysis on the capacity threshold, which indicated that the Swedish network, as modelled here, had, albeit barely, enough capacity to cope with the demand projected for the analysis period.

Further to the previous point, Scenario 3 (No Slab Track) has a significantly better result than Scenarios 1 or 2, further suggesting the limited or no benefit of the introduction of slab track in this case study. A more detailed analysis of specific bottlenecks could, however, reveal specific instances where this would be beneficial.

The fact the Scenario 4 stands out raises another important issue, that of average speeds. Indeed, a relatively modest increase in average speed can bring huge benefits to users and to society. This is all the more true when we recall that the model uses a lower bound for the value of time of a portion of the freight being transported on the rail, namely, the transferred freight.

Finally, due to limited data, we have not included the analysis of delays in all scenarios. However, the analysis made with Scenario 1 and estimated delay values, also show how potentially important it can be to act on this issue.

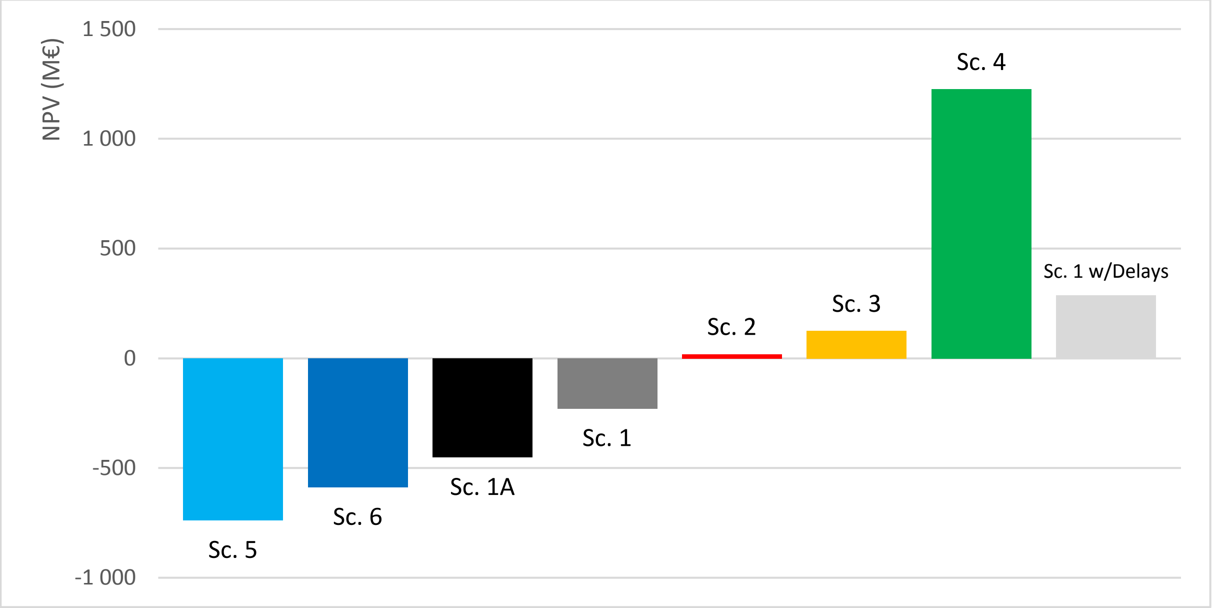

Figure 10. Ranking of C4R Scenarios for Sweden Case Study

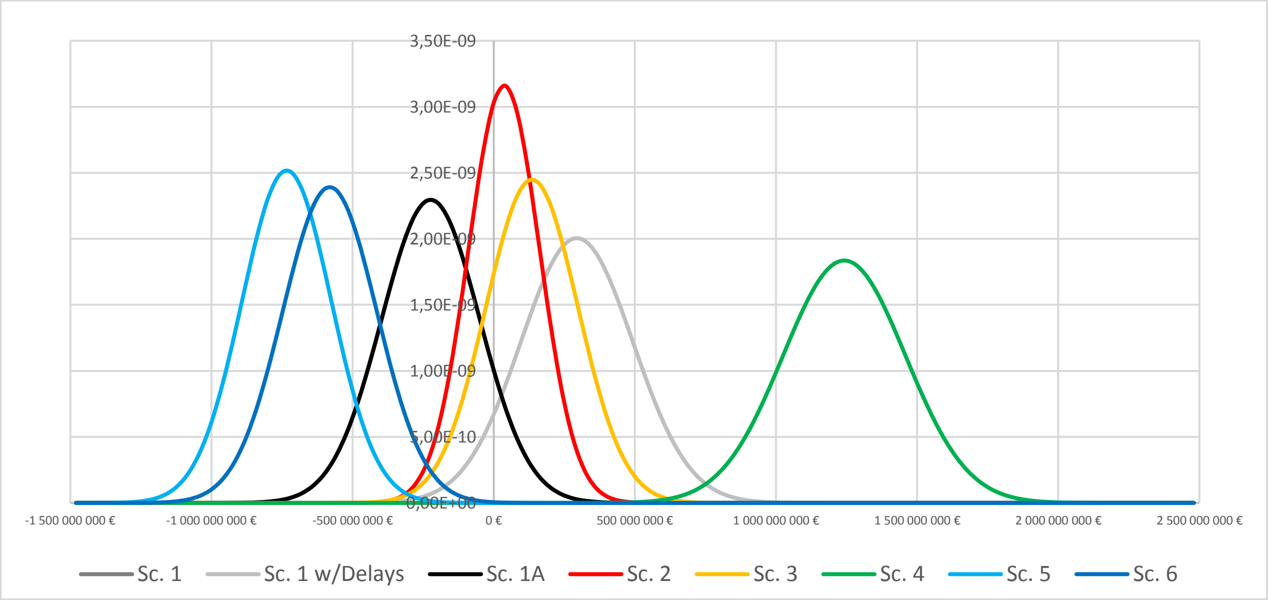

Figure 11. Ranking of C4R Scenarios for Sweden Case Study with probabilistic distributions (smooth curves).

4.2 RANKING OF SCENARIOS FOR MONTPELLIER-PERPIGNAN CASE STUDY

Using a similar approach to the previous case study, we summarize the results for the Montpellier-Perpignan case study. The set of scenarios is slightly different, although we kept the numbering for scenarios with similar assumptions. In this case study, each scenario is further divided into two investment levels. To recall all the scenarios:

- Scenario 1:
  - Investment Level 1: Siding extensions and trains up to 1000 m;
  - Investment Level 2: All infrastructure innovations and trains up to 1500 m.
- Scenario 3:

  - Investment Level 2: Implementation of Switches and Crossings' innovations, without Slab Track introduction.
- Scenario 5: Road Positive scenario, with the introduction of new trucks with smaller operating costs from 2030.

The main result to highlight here is that all scenarios result in a positive NPV. This is very possibly due to the fact that this section is capacity constrained and works as a bottleneck for the corridor. The consequence is that any investment that increases rail capacity will have a much higher chance of having an overall positive economic impact. The difference between Investment Level 2 in Scenarios 1 and 2 allows us to isolate the effect of the slab track investment. Albeit small, this shows it has a positive impact in this case.

Unsurprisingly, any innovation that reduces road operating costs leads to a smaller return on investments on the rail, since it cuts into the benefits arising from modal transfer from road to rail. However, with a unit operating costs reduction benchmarked from the Swedish case study, this corridor still shows a positive NPV in the Road positive scenarios.

The probabilistic results in Figure 13 show that Investment Level 2 always has a larger degree of uncertainty. This is mainly due to the uncertainty in the slab track investment costs.

As a final general comment, bearing in mind the differences between this and the previous case study, we would argue that these results show there can be no universal solutions for the rail networks. The potential benefits from the introduction of infrastructure innovations, in particular, vary widely depending on the conditions of each corridor or section.

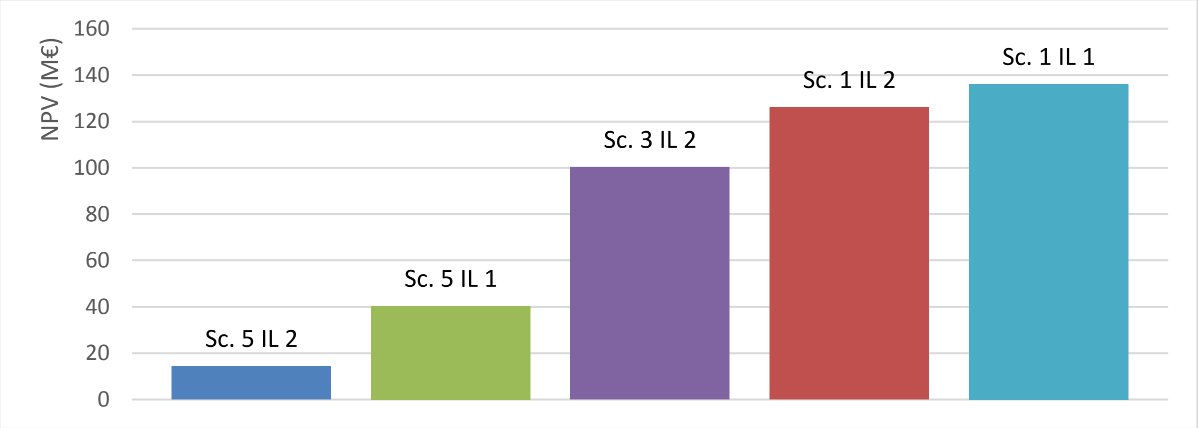

FIGURE 12. RANKING OF C4R SCENARIOS FOR MONTPELLIER- PERPIGNAN CASE STUDY

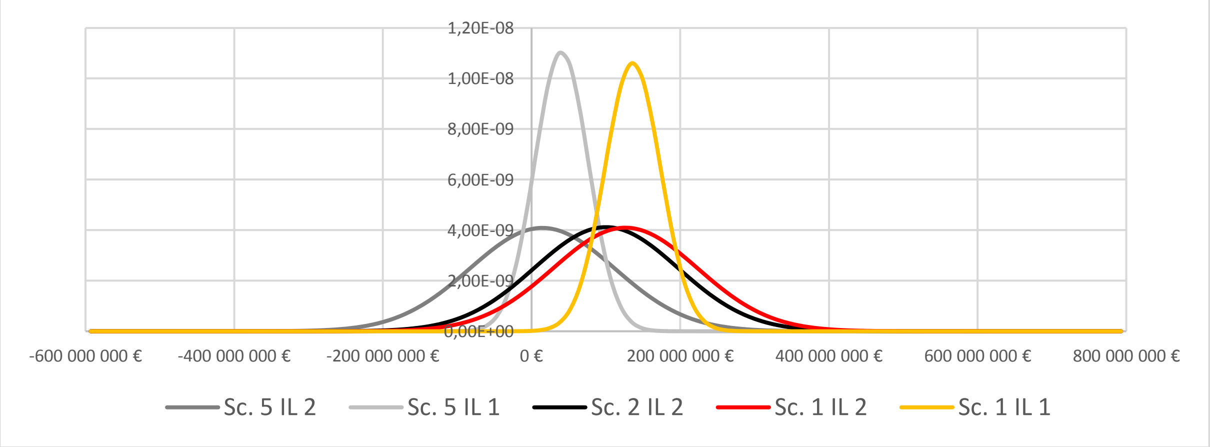

FIGURE 13. RANKING OF C4R SCENARIOS FOR MONTPELLIER- PERPIGNAN CASE STUDY WITH PROBABILISTIC DISTRIBUTIONS (SMOOTH CURVES).

5 Conclusions

The two case studies here presented, although different in scope, both produced very rich results and allowed for interesting analysis and discussion.

From all the preceding discussion, we would take two main points on the economic impacts of the innovations that have been considered in the context of the Capacity4Rail project.

The first point to be taken is that deep infrastructure investments may or may not be profitable, depending on the conditions of the corridor. What becomes apparent from the results presented here is that there is a much higher chance of large investments, such as upgrade to slab track, being profitable in capacity constrained sections. However, local boundary conditions, which have big impact on investment cost, complexity of upgrade and operational risks must be necessarily considered in decision making. It should, however, be noted that the biggest share of the benefit is generated by gains in availability leading to increased capacity.

The second point concerns the very high profitability that the introduction of innovative operational concepts may have. We are talking about rolling stock innovations, such as automatic couplers, EP brakes, often combined with modest infrastructure investment in siding extensions to allow for longer and heavier trains.

In both the preceding issues, the main benefits generating mechanism is the modal transfer from road to rail that is allowed by the increased carrying capacity. Benefits in other categories are usually small in comparison. Still, some of the analysed scenarios show that improvements in delays or reductions in travel times can have significant positive impacts trough savings in value of time.

Further considerations deriving from the results of these case studies are made in Deliverable D5.6.1, specifically, concerning the European policy Targets and Roadmap as well as market share perspectives.

6 References

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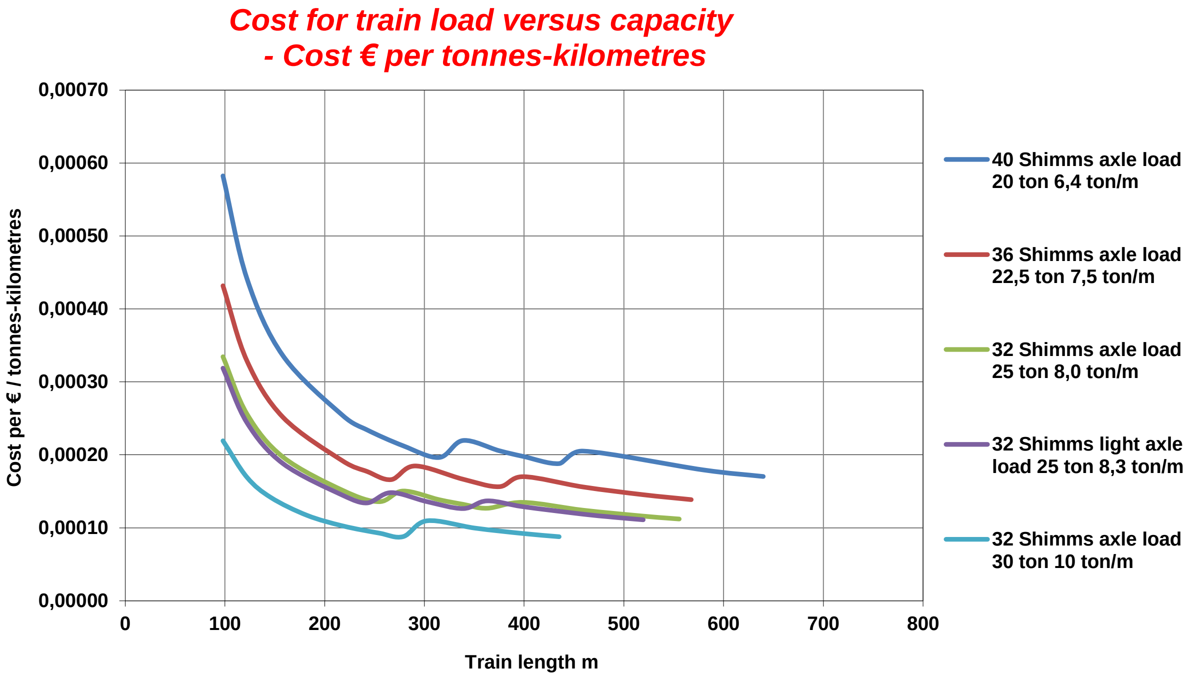
[7] Trafikanalys, “Punktlighet på järnväg 2016,” 2017.

APPENDIX - Parameters for capacity and costs of freight trains in Sweden including



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Executive summary

This report define input to scenarios for future freight trains 2030/2050 which have been used as an input in SP5 for cost-benefit calculations (CBA) for the Scan-Med Corridor RFC3 made by IST (Instituto Superior Tecnico).

The aim is to describe the RFC3 corridor itself in Sweden and possible future development on basis of forecasts, plans and visions as well how it will affect costs and capacity with longer and heavier trains as well as improved freight wagons. The freight wagons are the same as has been described in MS 15: Scenarios of Development of new rail freight vehicles. In this report is also included as a component in the cost calculations MS23: Business cases and validation for WP2.2: Novel rail freight vehicles.

At first forecasts which has been used in evaluation of RFC3 in Sweden is described. The forecast has been made for Trafikverket (the Swedish infrastructure manager) by KTH. The baseline forecast up to 2030/2050 for all modes is presented but in this project forecasts for rail freight up to 2030 has been used. The increase for rail freight transport from 2010-2030 is 1.3 % per year and the market share is constant at 25 %. Wagon load is decreasing but train load and inter modal is increasing its share of rail freight in this forecast.

The number of trains is also calculated on the rail network and detailed data for each link and products has been delivered to D5.4.2/3. Some specific data for delays and some data of the future performance of RFC3 are described i.e. train lengths. Today the normal train length is 630m in Sweden but Trafikverket plans for 750 m train lengths in 2030. As a long term scenario 1050 m train length has been assumed. A dedicated high speed network is planned in Sweden which will affect RFC3 between Stockholm and Malmö/Copenhagen.

Capacity analysis which has been done at KTH shows that when dedicated high sped lines will be built, most of the express trains can be removed from Stockholm-Malmö and Stockholm-Gothenburg lines. In addition to extremely short travelling times and greater capacity and punctuality in passenger traffic, capacity is also freed up on the old main lines for freight traffic and regional trains. Simulations show that it is possible to operate 2-3 times more freight trains during day time.

KTH cost models has been used for evaluations of capacity and costs of freight trains and freight wagons. The cost model is a train cost model in which different production systems can be calculated. In another EU-project, the VEL-wagon, the model has been completed with a wagon costs-model in which different wagon types can be tested, both existing and hypothetical. Also transportation costs for transport chains can be calculated and compared with truck transports. Some examples of how break-even point between rail and direct truck transports will be affected of different measures are shown in chapter 6.

Then the effects of longer and heavier trains are described. An example from the line between Germany and Denmark in the relation Maschen and Fredericia is described. The

train length was increased from 650 to 835 meter, the train weight was increased from 1,600 up to 2,300 metric tons between 2010 and 2013. The increase of utilization of about 19 % led to a decrease of costs per unit by about 14 %. The strengthened competitiveness led to an increase of market share by more than 25 %.

A train length of 1,050 m is an optimal train length because a modern 4-axle electric loco can haul 2,200-2,600 gross tonnes and intermodal train weights approximately 2 tons/meter. That means that 1,000 m wagon rake weight 1,000x2= 2,000 tons with a marginal for variations and heavier freight. That´s why a total train length of 1,050 m incl. locomotive are a good alternative for freight corridors which can be introduced on long term.

Then the effects of longer trains in terms of capacity and transport costs per net tonnes kilometres are shown for 630, 750, 835 and 1050 m long trains. This are calculated for wagon load and inter modal trains for containers and trailers. From 630 to 1050 m the capacity per train increases in the order of 70 % and the cost decrease with 20-30 % per net tonne kilometre.

For train load with high density goods, the train length is mostly not a restriction but the train weight is more important. Modern locomotives have a tractive power of 5-6 MW capable of hauling 2,000-2,600 tonne. Not only the tractive power but also the locomotives' axle load is critical for optimal traction. But most locomotives are originally constructed for passenger transports with relatively low axle load. To increase the axle load from normally around 20 tonnes to 22.5 or 25-30 tonnes for heavy haul is therefore an option. The calculations shows that one 6-axle locomotive with 25 tonnes axle load, which is permitted for the wagons on some lines used today, can haul approximately the same train weight as two 4-axle locomotives with 21 tonnes axle load.

Finally the wagons evaluated in WP2.2. and MS15 have been evaluated. The 12-axle container wagon for 40 feet containers means 7 % improvement of capacity for a full train of 740 meter as well as 7 % less cost per tonnes kilometres compared with a 6-axle wagon. Wagons for non-liftable trailers as Modahlor and Megaswing give a higher cost than wagons for liftable trailers but widen the market for trailer transports and means that there is no need for lifting equipment on the terminals. The 6-axle car transport wagon developed in WP2.2. has 9 % higher capacity and 10 % lower cost than a 4-axle car transport-wagon.

For heavy load with steel transport wagons higher axle load from 20 tonnes up to 30 tonnes is evaluated. The importance of higher axle load is evident. To increase the axle load from 20 to 25 tonnes means 34 % higher capacity per wagon and 10 % decreased cost per net tonnes. A light weight wagon with 25 tonnes axle load can increase the capacity with 37 % and decrease the cost with 12 %.

For high-cube wagon load wagons the importance of a wide gauge is showed. The advantage of a large gauge is shown by a 4-axle US box-car which has 73 % higher capacity and 40 % lower cost per m^3 than an ordinary European wagon.

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1 Introduction

1.1 Aim

The aim of this report is to define scenarios for future freight trains 2030/2050 which can be used as an input in SP5 for cost-benefit calculations (CBA) for the Scan-Med Corridor RFC3 made by IST (Instituto Superior Tecnico).

The aim is to describe the RFC3 corridor itself in Sweden and possible future development on basis of forecasts, plans and visions as well how it will affect costs and capacity.

In this report is also included MS23 Report “Business cases and validation” for WP2.2 “Novel rail freight vehicles” as a component in the cost calculations.

1.2 Method

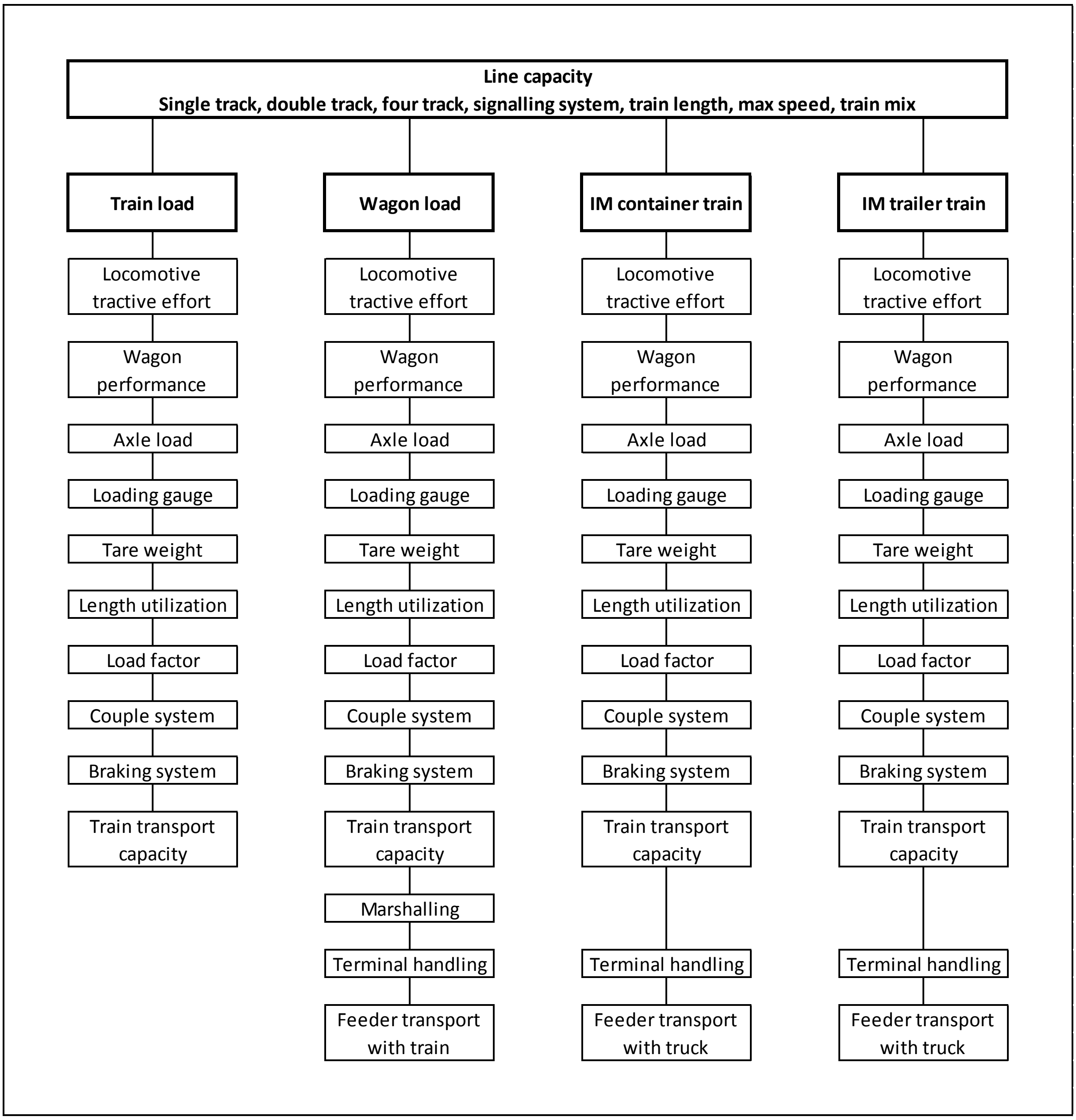
To do this the following method has been used:

1. A starting point is the future freight train system defined in the summary of the SP2 WP2.1 “Requirements toward the freight system of 2030/2050”
2. The line capacity and train capacity has been defined in SP3 WP 2.1 report “Line capacity and train capacity for future freight corridors”
3. The capacity performance of improvements of future freight wagons has been evaluated in the report of SP2 WP 2.2 MS 15 “Scenarios of Development of new rail freight vehicles”
4. The parameters for analysis of capacity of freight trains in this report have been defined according to figure 1.1.
5. The parameters in figure 1.1 have been defined for Sweden and specific for the lines in RFC3 Scandinavian- Mediterranean Corridor.
6. Cost calculations have been done by cost models developed by KTH and in the VEL-wagon-project reported in D 3.1 “Study on railway business for VEL-Wagon and target costs” and D 5.2 “Implementation and migration strategy” (EU Grant agreement no: 265610).
7. Effects on cost and capacity for longer and heavier trains have been evaluated by KTH cost models
8. Cost calculations have been made for the same wagons as in SP2 WP 2.2 MS 15 and is presented in chapter 8 as MS23 “Cost and Capacity for different wagons”.

1.3 Delimitation

Many data has been transferred to IST in detailed spread-sheets which are not included in this report. Here the background to the figures is presented and some general cost and capacity relations are analysed. The scenarios for CBA-analysis and the results are presented in D6.4.2/3 “Assessment of technologies, scenarios and impacts by IST reviewed by DB:

Figure 1.1: Scheme for analysis of capacity in future freight rail corridors



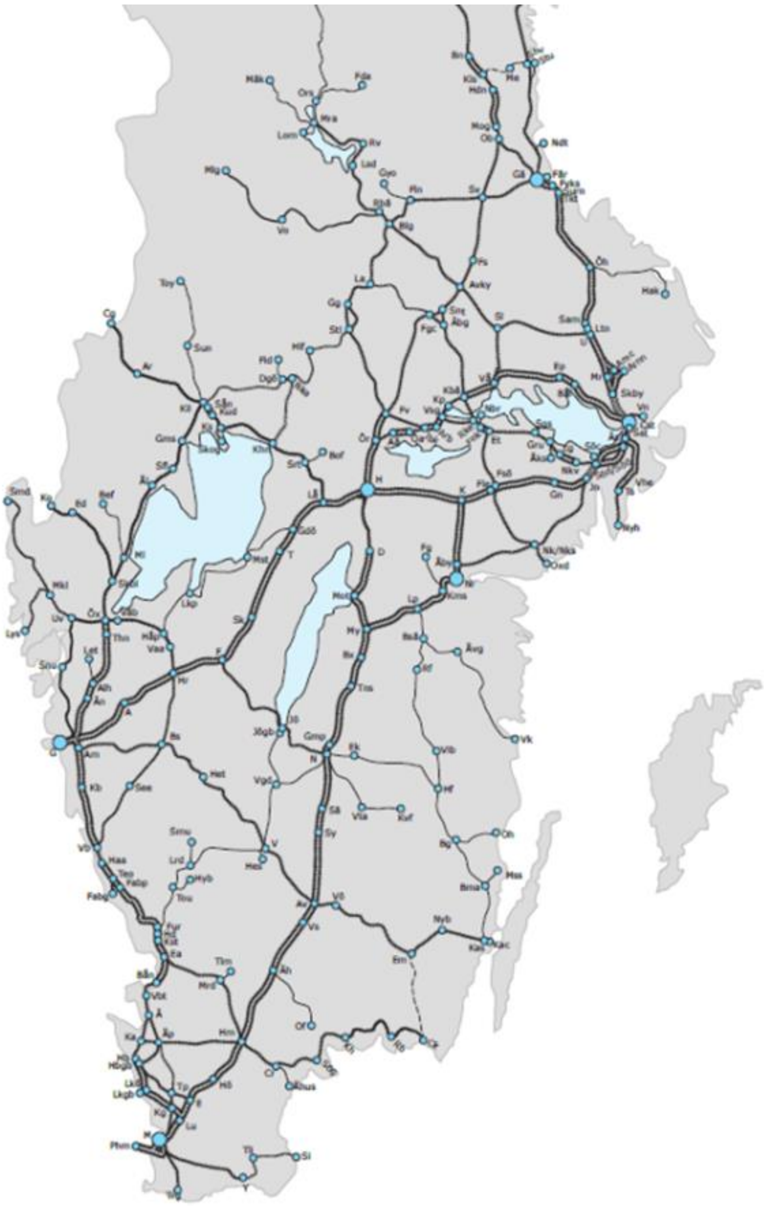


Figure 1.2: Rail network in southern Sweden.

2 Scenarios for future freight trains 2030-2050

WP 2.1 Requirements toward the freight system of 2030/2050

The main objective of work package WP2.1 was:

- To describe today's and future demand for rail freight through existing forecasts and describe scenarios for freight flows up to 2050
- Analyse existing and expected future customer requirements for different goods segments
- Analyse beyond state of the art for vehicles, intermodal systems and operation principles and identify gaps that remain to be successively bridged up to 2030/2050.
- To specify the requirements an efficient freight rail freight system by 2050 that can fulfil the EU targets

A report was published 2015-06-10. In the executive summary parameters for the future rail freight system 2030/2050 was outlined and also compared with todays´ system, see table 1. Some of the parameters are important to increase the line capacity, some are important to increase the train capacity and then there are parameters which is important to increase quality and lower the cost for rail freight.

Summary of WP2.1 Requirements for the future rail freight system

Most forecasts show an increase of 60% in total freight demand by 2050 and an approximately constant market share with a business-as-usual scenario. To fulfil the targets in the EU white paper, it is necessary to roughly double rails' market share from 18% in 2011 to at least 36% in 2050. This means that the tonne-kilometres will be 3.6 times as much as today and 2.4 times as much as in a business-as-usual scenario in 2050.

To reach the white paper target, it is necessary to both increase quality and capacity and lower the cost of rail freight. The customers must be able to trust the delivery time to meet the requirements of their logistic chain and the cost must be competitive with road freight. A system approach is therefore needed and the critical development lines must be identified. From the customer's transportation needs that put demands on the wagons – the wagons are coupled together into trains where available tractive power is taken into account – the train utilises the infrastructure with a certain performance along a link and ultimately in a network from origin to destination.

Much of today's freight train system and infrastructure is based on an old standard 3-4 MW locomotive that means trains of approximately 1,500 gross tonnes and a train length of 650-750 metres. But modern locomotives have a tractive power of 5-6 MW capable of hauling 2,000-2,500 tonne trains of up to 1,000m in length. In Europe, train lengths up to 850m already exist and experiments have been made with 2x750m=1,500m long trains with radio-controlled locomotives in the middle of the train. Not only the tractive power but also the locomotives' axle load is critical for optimal traction. To increase the axle load from normally around 20 tonnes to 22.5 or for heavy haul, 25-30 tonnes is a possibility to operate heavier trains but must be combined with track-friendly bogies.

Concerning the wagons, one important question is whether development will be incremental, as it has been so far, or if it is possible to make a system change. An incremental change means successively higher axle loads, wider gauge, higher payload and less tare weight per wagon, better brakes like more silent brake-blocks, end of train devices and some electronic sensors. A system change will include electro-pneumatic brakes, disc-brakes, full electronic control of the wagons and load and automatic central couplers. The automatic couplers is the most critical component but important not only because it will make shunting and marshalling safer and cheaper but also because it will make it possible to operate longer trains without problems and introduce electronic braking systems. It will be easier to feed the train with electricity and signals and to build lighter wagons and lower the floor.

Today, most rail operators use electric locos for long haul and diesel locos for feeder transport and terminal shunting. But the duo-loco has now been introduced into the markets, equipped with both normal electric traction and diesel traction, either for shunting or for line haul. This means that a duo-loco can shunt the wagons itself at a marshalling yard or stop at an un-electrified siding at an industry and change wagons directly. The operators thus need only one loco instead of two and it will also make it possible to introduce new operation principles like liner trains which can stop along the line and change wagons. It will also decrease vulnerability in case of current interruptions. In the long term, it will also make it possible to avoid catenaries at marshalling yards and sidings, which will save money for the IM.

Also for intermodal it is an advantage to introduce liner trains. If the terminals are located on an electrified side track where the train can drive straight in and out onto the line again, there is no need for a diesel loco to be switched in. This in turn requires a horizontal transfer technology that can function under the overhead contact wires. The train must be able to be loaded and unloaded during a stop of 15-30 minutes. This also obviates the need to park wagons. The terminals can also be made more compact and require less space. This will reduce the costs which is critical for intermodal.

Most trailers today are not designed to be lifted onto a railway wagon. The trailer market is in practice therefore very limited even at conventional intermodal terminals that have lifting equipment. Solutions where trailers do not need to be lifted but can be rolled on and off along a ramp can thus widen the market considerably. They also mean that simple terminals only need to be dimensioned for the trucks’ axle load.

To increase the capacity of the rail system, the following measures can be taken: (1) More efficient timetable planning: On double track: Bundling of trains with the same average speed in timetable channels to harmonize speeds. During the day faster freight trains are an option. (2) Use of trains and vehicles with higher capacity: For freight: Longer trains, higher and wider gauge, higher axle load and metre load. For passenger trains: Double-decker and wide-body trains. (3) Differentiation of track access charges to avoid peak hours and overloaded links. (4) Better signalling system, shorter block lengths and in the long term introduction of ERTMS level 3. (5) Adaptation of freight corridors for long and heavy freight trains. (6). Investment in HSR to increase capacity for freight trains and regional trains on the conventional network and in some cases dedicated freight railways.

There is a target in the white paper to triple the length of HSR by 2030, which means approx. 18,000 km HSR or 8% of the rail network. According to actual plans, this seems to be realistic. The planned

Rail Freight Corridors (RFC) are of approximately the same length. However, there is no common plan to increase the standard in the RFC, which would be desirable. With the measures listed above, longer and heavier trains will make it possible to roughly double the capacity for freight trains without building new railways and in the long term with ERTMS level 3 even more.

Figure 2.1: Today´s common standard, incremental change and system change from WP2.1.

Equipment	**Common standard**	**Incremental change***	**System change***
Wagons			
Running gear	Different	50% Track-friendly	All track-friendly
Brakes	Cast brakes	LL brakes	Disc brakes
Brake control	Pneumatic	Radio controlled EOT	Fully electronic
Couplers	Screw couplers	Automatic couplers on some trains	Automatic couplers on all trains
Max Speed	100 km/h	120 km/h	120-160 km/h
Max Axle load	22.5 tonnes	25 tonnes	30 tonnes
Floor height lowest	1,200 mm	1,000 mm	800 mm
IT-system	Way-side	Some in wagons	All radio controlled
Locomotives			
Tractive effort kN	300	350	400
Axle load	20 tonne	22,5 tonne	25 tonne
Propulsion	Electric	Some duo-locos	All duo-locos
Fuel	Diesel	LNG/Diesel	LNG/electric
Drivers	Always drivers	Some driverless	All driverless
Trains			
Train lengths in RFC	550-850 m	740-1050 m	1050-2100 m
Train weight	2,200 tonnes	4,400 tonnes	10,000 tonnes
Infrastructure			
Rail Freight Corridors	18,000km	25,000km	50,000km
Signalling systems	Different	ERTMS L2 in RFC	ERTMS L3 in RFC
Standard rail weight	UIC 60 kg/m	70 kg/m	70 kg/m
Speed. ordinary freight	100 km/h	100-120 km/h	120 km/h
Speed, fast freight	100 km/h	120-160 km/h	120-160 km/h
Traffic system			
Wagonload	Marshalling - feeder	Marshalling – feeder Some liner trains	Automatic marshalling Liner trains – duo-loco
Trainload		Remote controlled	All remote controlled
Intermodal	Endpoint-trains	Endpoint-trains Liner trains with stops at siding	Endpoint-trains Liner trains fully automated loading
High Speed Freight	National post trains	International post and parcel trains	International post and parcel train network
IT /monitoring systems			
	Some different	Standardized	Full control of all trains and consignments

*) Adapted to market needs in each product and line

3 Forecasts for freight transports in Sweden

3.1 Forecast for the total transportation effort

For this project a forecast has been used which has been done for Trafikverket for the total transport market in Sweden with modal split from 2010 to 2030-2050 [2]. This forecast also included a distribution of the rail transport products in terms of wagon load (WL), train load (TL), Inter modal (IM) and iron ore (IO) transports as well as the need for capacity on marshalling yards. This forecast is also input for calculation of the number of trains on different sections on the railway network showed in chapter 4.

The main results are shown in table 3.1. and figure 3.2-3.3. Rail transport will increase with 28 % up to 2030 and the market share will be constant at 25% for the long distance transports >100km.

Tabel 3.1: Freight transportation effort for 1990, 2010 and 2013 and baseline forecasts for 2030 and 2050 with modal split for long distance transports >100 km and growth for periods.

Tonnes kilometres billions				Baseline forecast		Increase		
	1990	2010	2013	2030	2050	1990-2010	2010-2030	2030-2050
Long distance								
Rail	18,8	22,5	21,1	28,9	33,8	20%	28%	17%
Domestic shipping	8,3	7,8	6,7	9,8	11,5	-6%	26%	17%
International shippir	19,3	26,6	26,1	31,8	37,8	38%	20%	19%
Truck	21,2	32,2	30,8	46,5	59,7	52%	44%	28%
Sum	67,6	89,1	84,7	117,0	142,8	32%	31%	22%
Short distance								
Truck	8,0	7,5	6,4	10,8	13,3		44%	23%
Total	75,6	96,6	91,1	127,8	156,1	28%	32%	22%
Share of long distance						***Increase % per year***		
Rail	28%	25%	25%	25%	24%	0,9%	1,3%	0,8%
Domestic shipping	12%	9%	8%	8%	8%	-0,3%	1,1%	0,8%
International shippir	29%	30%	31%	27%	26%	1,6%	0,9%	0,9%
Truck	31%	36%	36%	40%	42%	2,1%	1,9%	1,3%
Sum	100%	100%	100%	100%	100%	1,4%	1,4%	1,0%

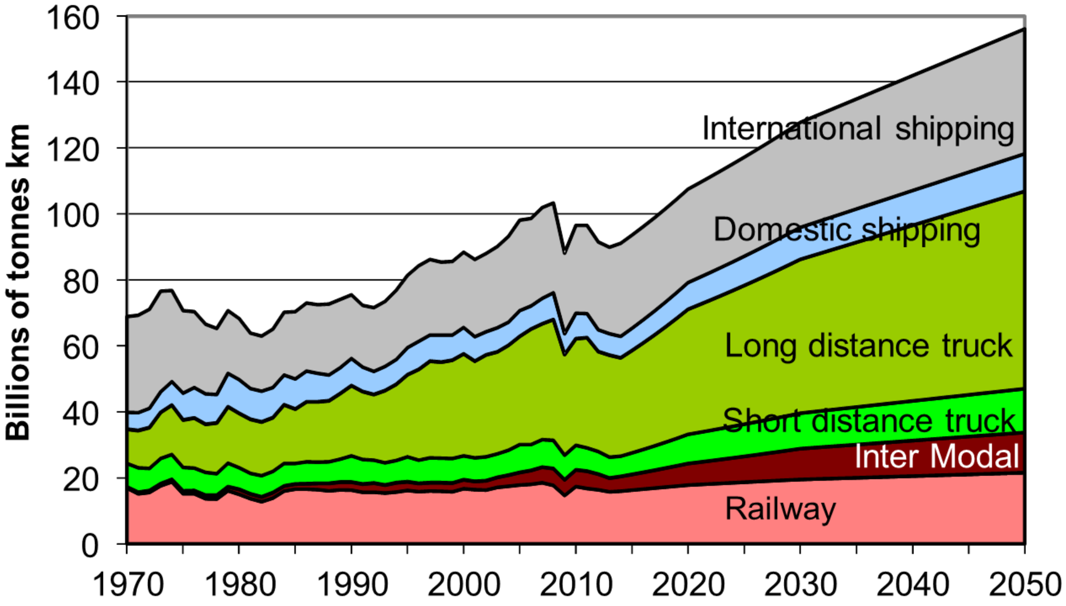


Figure 3.2: Development of the total transportation effort 1970-2014 and forecast for 2030-2050 for a baseline alternative.

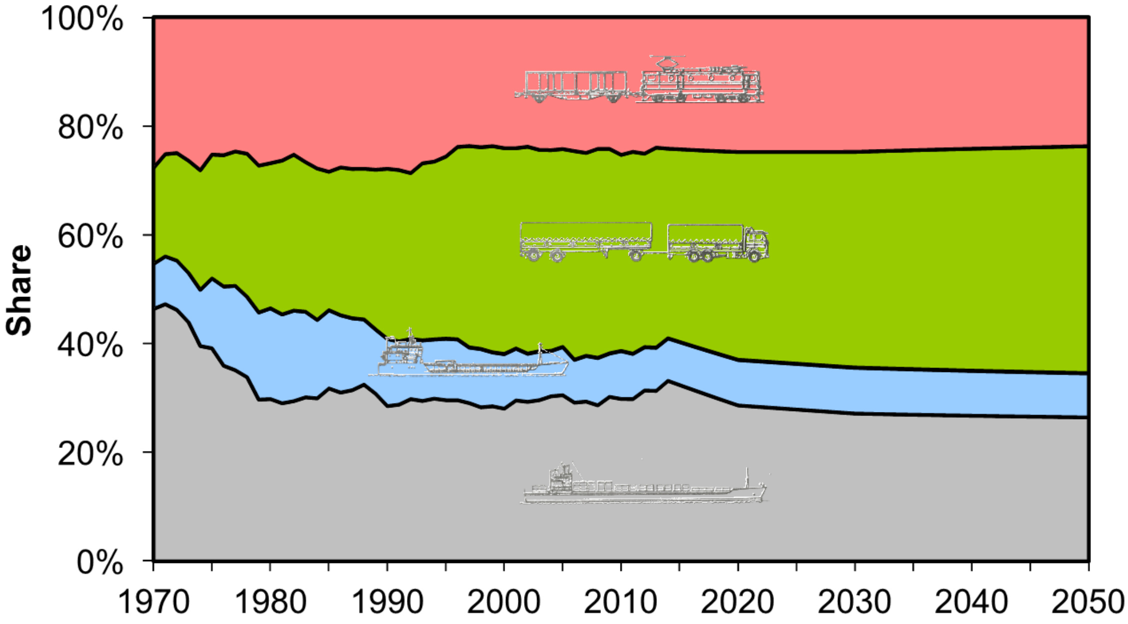


Figure 3.3: Modal split of the total transportation effort 1970-2014 and forecast for 2030-2050 for a baseline alternative.

3.2 Forecast for the different rail products

The development of Wagon load, Train Load, Inter Modal and Iron Ore transports are shown in table 3.4 and figure 3.5-3.6. In baseline forecast Wagon Load will successively decrease and Train load and Inter Modal will increase. Iron Ore transports are dedicated to the Iron Ore line in northern Sweden and will not affect the other network. The other products will affect RFC3 in the same way as in the general forecast.

Tabel 3.4: Freight transportation effort for 1990, 2010 and 2013 and baseline forecasts for 2030 and 2050 with modal split for rail products in Sweden and growth for periods.

Tonnes				Baseline forecast		Increase		
kilometres billions	1990	2010	2013	2030	2050	1990-2010	2010-2030	2030-2050
Products								
Wagon Load	9,8	6,7	6,3	6,6	7,5	-32%	-1%	13%
Train Load	3,3	6,2	5,6	9,0	10,4	85%	45%	16%
Inter Modal	2,4	5,0	4,5	7,8	9,1	109%	56%	16%
Iron Ore Line	3,2	4,6	4,8	5,5	6,8	44%	19%	24%
Sum	18,8	22,5	21,1	28,9	33,8	20%	28%	17%
Short distance								
Truck	8,0	7,5	6,4	10,8	13,3		44%	23%
Total	26,8	30,0	27,5	39,7	47,1	12%	32%	19%
Share of products						***Increase % per year***		
Wagon Load	52%	30%	30%	23%	22%	-1,9%	-0,1%	0,6%
Train Load	18%	27%	26%	31%	31%	3,1%	1,9%	0,8%
Inter Modal	13%	22%	21%	27%	27%	3,8%	2,2%	0,7%
Iron Ore Line	17%	21%	22%	19%	20%	1,8%	0,9%	1,1%
Sum	100%	100%	100%	100%	100%	0,9%	1,3%	0,8%

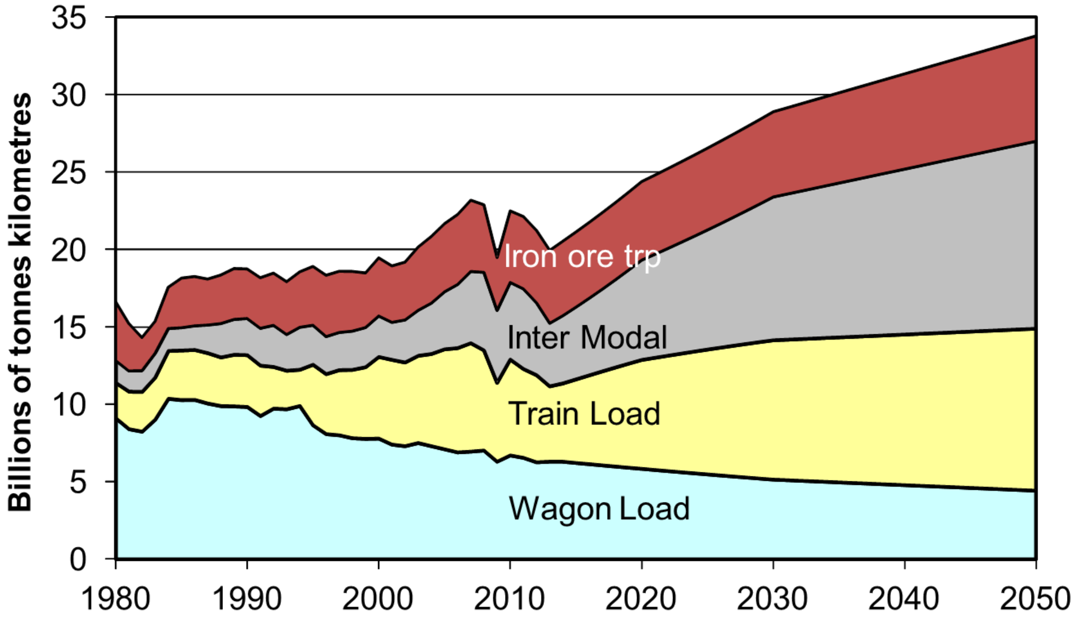


Figure 3.5: Development of the rail freight transportation products 1970-2014 and forecast for 2030-2050 for a baseline alternative.

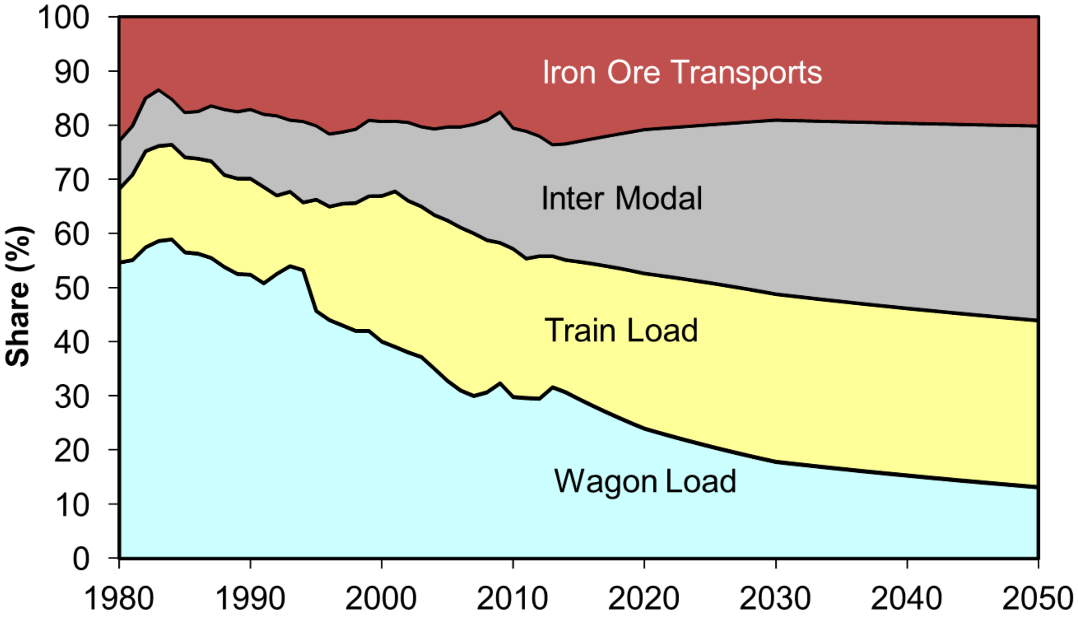


Figure 3.6: Distribution of the rail freight transportation products 1970-2014 and forecast for 2030-2050 for a baseline alternative

4 The number of trains and performance of the rail network

4.1 Forecast for the number of freight trains on the network

A method has been developed at KTH to calculate the number of freight trains on different sections of the rail network. The basis is the number of freight trains on the network at the starting year, in this case 2010, and a matrix for the transport volumes between the counties for the starting year and the forecast year. The freight volumes will be assigned to the network by the tool VISUM considering the shortest transport time through the network. A quota will be calculated between the forecasted volume and the volume at the starting year on each link in the network.

With this quota the number of freight trains will be calculated on each link. The railway network is divided in 167 sections to be able to show figures on maps. Special routines have been worked out to calculate the number of trains on inside a county with no passing traffic. It is also possible to implement new links in the system which can be used by freight trains if they are faster because of higher capacity. One example is the fixed link via Fehmarn Bält. It is also possible to adjust the number of freight trains if they will be longer and heavier but this has not been done in this case.

A map with the number of freight trains at 2010 is shown in figure 4.1 and a baseline forecast for 2030 in figure 4.2. The number of trains is the planned paths for freight trains, the operated number of trains are usually lower for freight trains. All freight trains are included, also local feeder trains which operate over a section. The number of trains is symmetric, the number of trains per direction has been summarised and divided with two, because the number can be distributed by temporary variations per direction on the actual day for measuring the number of trains.

The number of freight trains will increase with 30 % in the baseline alternative exclude the iron ore transports. Please notice that the number of freight trains is an increase in proportion to the number of tonnes depending on the demand. No consideration to the possibility to operate heavier trains, longer trains, to implement higher axle loads or wider gauge, measures which in practice will reduce the number of trains.

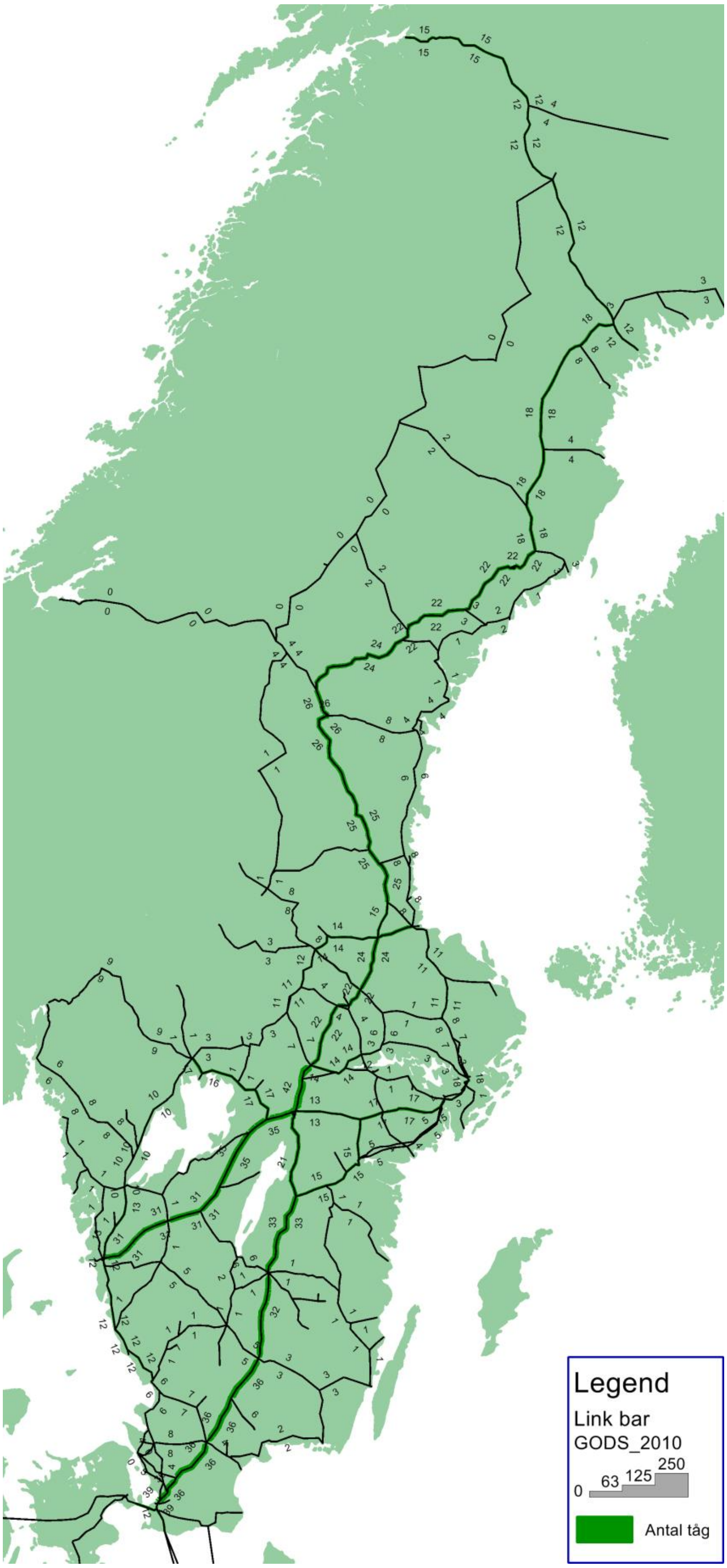


Figure 4.1: Number of freight trains per section and direction on the railway network in Sweden 2010. The figures are planned trains, the actual number of operated trains are lower.

Figure 4.2: Number of planned paths for freight trains per section and direction on the railway network in Sweden, baseline forecast for 2030.

4.2 Forecast for the number of passenger trains on the network

For passenger trains a map of the number of trains at 2010 is shown I figure 4.3. The same network and sections has been used as for freight trains. The baseline forecast is done on basis of Trafikverkets investment plan for the infrastructure development and plans from operators and public transport authorities. The baseline forecast is shown in figure 4.4.

For trains which cross the borders only passenger trains which operate direct from Sweden to Copenhagen, Oslo, Trondheim and Denmark is included. Other trains on links inside Norway and Denmark are not included.

The number of passenger trains is more decided by the supply and is in high degree dependent on the plans from public transport authorities. In this plans regional development with contribution of fast regional trains with high frequency is a prerequisite. Any control of capacity utilisation and demand has not been done in this calculation but is done in a separate forecast model.

4.3 Forecast for the total number of trains on the network

The total number of planned freight and passenger trains per direction at 2010 and for the baseline forecast at 2030 is shown in figure 4.5 and 4.6. Red is passenger trains on the line and green is freight trains outside the passenger trains, the total width of each section shows the total number of trains.

Notice that the number of freight trains is decided from the forecasted demand of freight transports and the number of passenger trains is more decided from the supply side according to actual plans. The number of freight trains can, and my probably, be reduced because of heavier and longer trains and other capacity measures. Also passenger trains can be reduced by longer, higher (double-deckers) and wider (wide-body trains) but the frequency is much more important for the customers on the passenger market than on the freight market.

On the other hand the frequency of passenger trains is very high because of deregulation of the long-distance market and at the same time ambitious plans from the regional authorities. So in practice the number of passenger trains maybe lower, and also the number of freight trains because the plans to operate longer freight trains.

Figure 4.3: Number of passenger trains per section and direction on the railway network in Sweden 2010. The figures show the planned paths.

Figure 4.4: Number of planned paths for passenger trains per section and direction on the railway network in Sweden, baseline forecast for 2030.

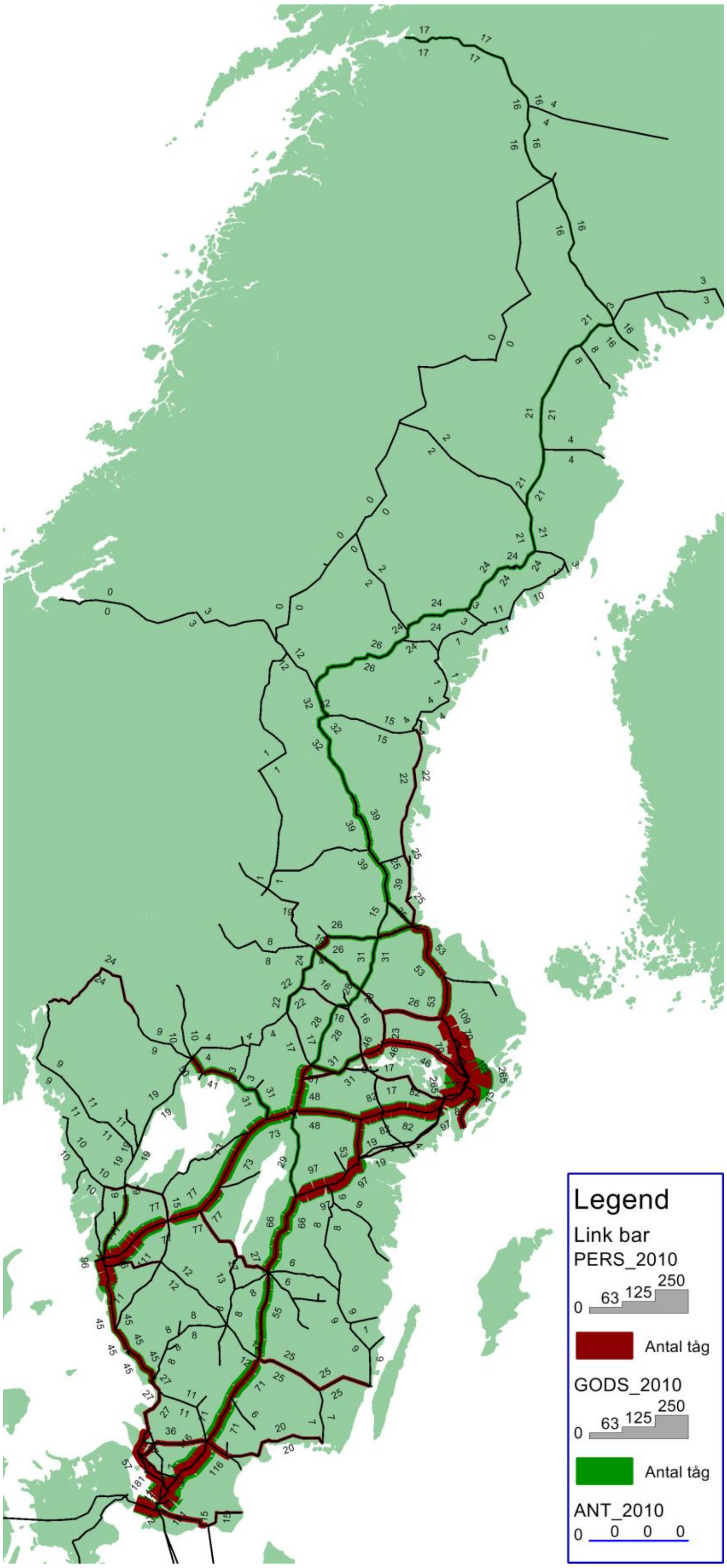


Figure 4.5: Number of passenger and freight trains per section and direction on the railway network in Sweden 2010. The figures show the planned paths. Red is passenger trains and green is freight trains which is added to the passenger trains. The total width is proportional to the total number of trains.

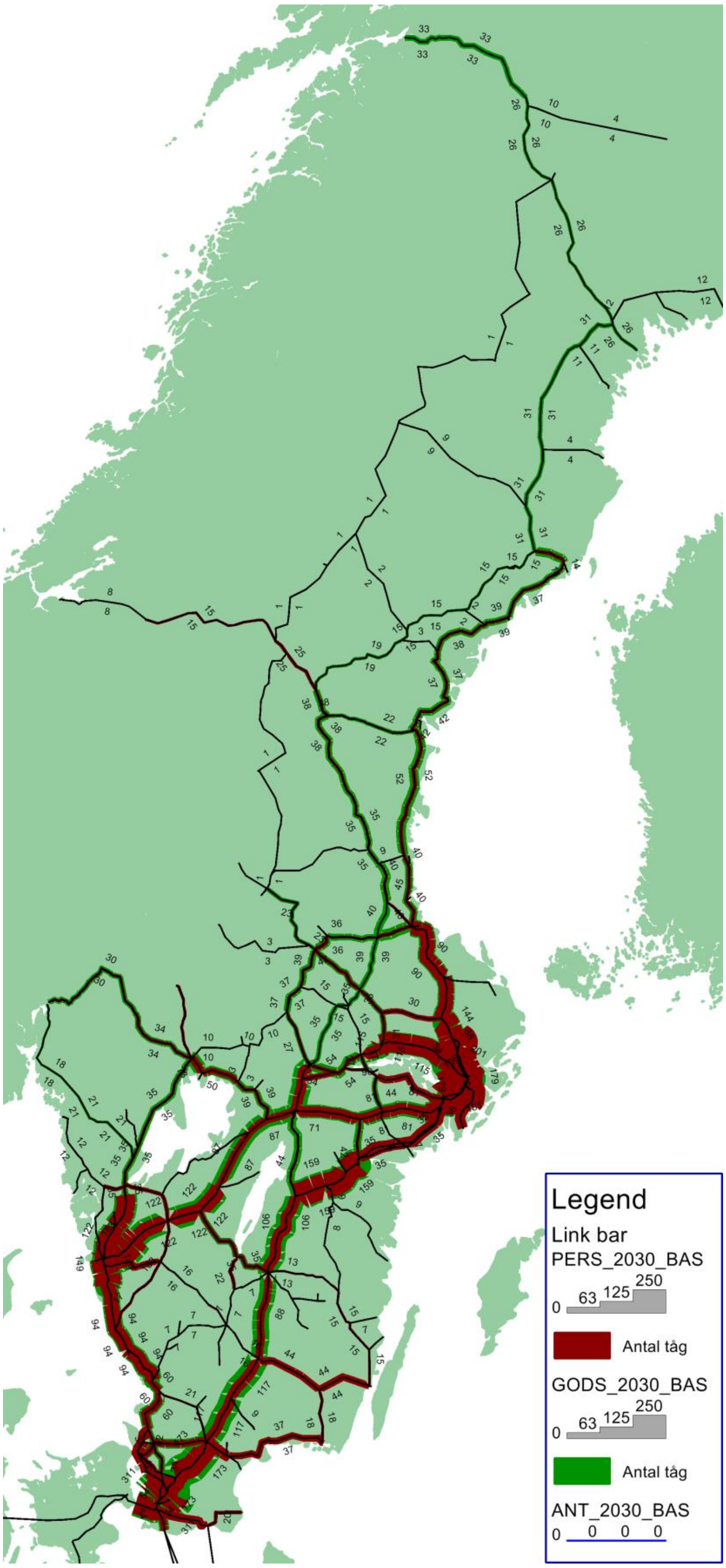


Figure 4.6: Number of passenger and freight trains per section and direction on the railway network in Sweden, baseline forecast for 2030. The figures show the planned paths. Red is

passenger trains and green is freight trains which is added to the passenger trains. The total width is proportional to the total number of trains.

4.4

4.5 Database over network performance

Data from several of Trafikverket's databases have been used to draw up a description of Sweden's rail network. This is published in "Railway capacity analysis - Methods for simulation and evaluation of timetables, delays and infrastructure" –PhD-thesis by A. Lindfeldt 2015.

Data from four different databases supplied by the Swedish Transport Administration is compiled into descriptive parameters covering different aspects of the network, such as infrastructure, timetable, train properties and delays. The rail network is divided into several line sections for which the parameters are calculated. The results are mainly presented as maps showing the network with the parameter values coded in colour or width of the line. The database has been used to describe network performance for RFC3 in Sweden.

The performance indicators are chosen in accordance to available data and with the intention to describe factors affecting available capacity, used capacity and symptoms of high capacity utilisation. In this case available, capacity is represented by infrastructure related indicators to some extent combined with the traffic data, like train length. The timetable is the main input for determining used capacity and delay symptoms of high capacity utilisation, as they are assumed to be capacity dependent. All calculated performance indicators are summarised in the table 4.7 below. Some example of results is shown in this chapter.

Table 4.7: Database structure, parameters and sources for the database.

Infrastructure	*Timetable*	*Traffic*	*Delays*
Single track: **Distance between crossing stations (km)** min max mean standard deviation Proportion of stations with more than 2 tracks Proportion of trains with simultaneous entry capability **Double track:** **Distance between passing stations (km)** min max mean standard deviation **All lines and stations (m)** Track length min mean max	**No. Trains per day** **Total/Passenger/Freight** No. Trains per day **No. Trains per hour** **Total/Passenger/Freight** Peak hour — Time for peak hour Morning — 06-09 Afternoon — 15-18 Afternoon — 16-17 Day — 9-15 och 18-20 Night — 20-06 **Speed (km/h)** **Passenger/Freight** max min mean median **Speed difference** standard deviation standard deviation/mean 95 percentile/10 percentile	**Freight trains** **Weight (metric tons)** min max mean standard deviation **Length (m)** min max mean standard deviation **No. Axles** min max mean standard deviation **Axle load** min max mean standard deviation **Gross tons/day (metric tons)** **Passenger trains** Proportion with ≤ 12 axles Proportion with > 12 axles	**Passenger/Freight** **Proportion of trains with increased delay** **Median of increased delay normalized by route distance [min/100 km]** **Standard deviation of increased delay normalized by route distance [min/100 km]**
Source: BIS **Measurement period** 2008-12-19	**Source:** T08.3 **Measurement period** 2008-10-09	**Source:** BANSTAT **Measurement period** 2008-10	**Source:** TFÖR **Measurement period** 2008-09 och 2008-10

Average speed and heterogeneity

The left map in figure 4.8 shows the mean speed based on all trains. In general double track lines have higher speeds than single track lines. This is due to both higher standard, but also because it is not necessary stop for crossings. RFC3 have high average speed.

The right map in figure 4.8 shows a heterogeneity measure: the 95 percentile divided by the 10 percentile, i.e. the quota of the mean speed for a fast train and a slow train, where a high value indicates a heterogeneous timetable and 1.0 a completely homogenous. Double track lines with a mix of passenger trains and freight trains have the most heterogeneous traffic like Katrineholm-Malmö in RFC3, where the value is higher than 2. The dense traffic on these lines increases the speed differences even more when freight trains have to stand aside for overtakings. The heterogeneity together with the number of trains operated per day gives a hint of the capacity utilisation on the double track lines, keeping in mind that especially freight trains and passenger trains might run during different periods of the day.

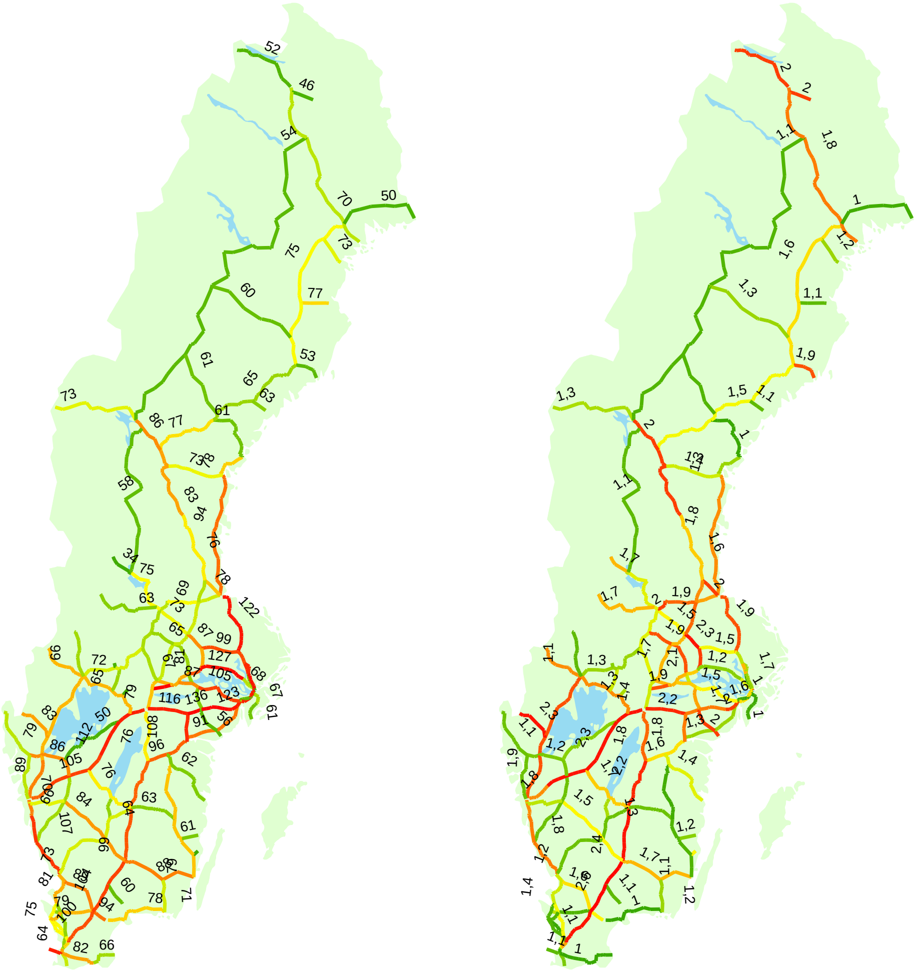


Figure 4.5: Left: Average speed [km/h] for all train types without service trains and shunting movements. Right: Mix of train speed ratio for all train types without service trains and

shunting movements. The figure is the ratio of the fastest train/slowest trains. For the fastest train it is the 95 percentile and for the slowest trains it is the 10 percentile.

Delays

The delay data is used to calculate the increase in delay for trains running along the whole section. It is necessary to look at the change in delay rather than absolute delay because most trains travel along several line sections. Based on the assumption that the change in delay is correlated to the length of the line section, the increased delay is normalised by the length of the section to make it comparable between different line sections. Figure 4.8 shows distributions of the delay development on a line section for passenger trains and freight trains.

The mean of the distributions are close to zero, and in the case of the passenger trains, slightly smaller than zero which is explained by allowance in the timetable that trains can use to reduce delay. Since the left hand side of the distribution is more closely correlated to available allowance than occurring delays, it is reasonable to focus on the right part, i.e. trains that have increased their delay. Note that many freight trains are ahead of the time-table.

The performance indicators based on the delay data is therefore the proportion of the total number of trains with increased delay, and median and standard deviation of the delay increase for the corresponding observations. The median is used rather than the mean to reduce the influence of few observations with very high delays. However, it should be clearly stated that allowances of course also helps to reduce the increase of delays, but by only looking at the positive values the effect of the allowances are somewhat reduced.

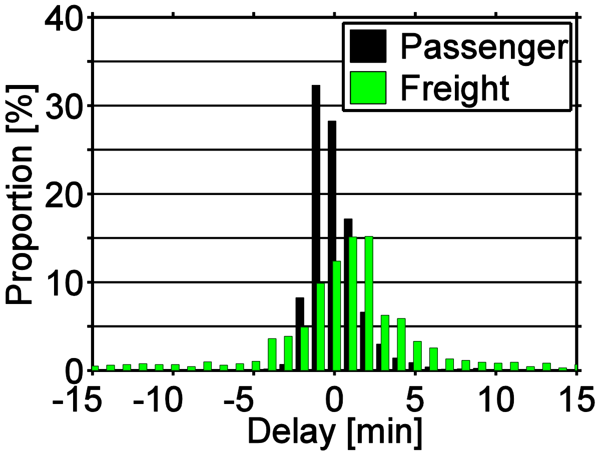


Figure 4.8: Example of registered delay development on a section of the Southern Main Line between Mjölby and Tranås on RFC3 (Sipilä, 2012). Distance of approximately 37 km. Period of measurement: 107 days

The left part of figure 4.9 shows the proportion of passenger trains that have increased their delay. The middle and right figures show the median of the delay increase per 100 km for passenger and freight trains respectively. The proportion of freight trains is within the same interval as for the passenger trains, but the median is much higher for the freight trains. The reason for this is the larger spread of the distribution for freight trains, figure 4.8. Line sections with a very high proportion of delayed trains indicate a systematic problem that affects all passing trains. This can be sections where the timetable has low allowances or congested areas where secondary delays easily occur and it is hard to recover due to congestion. Especially on congested single track lines, once a train is delayed, additional delays are probable due to frequent crossings. Some of the line sections with the highest proportion of delayed trains, up to 90 %, are due to temporary speed restrictions being active during the whole period of measurement. In these cases, the timetable have not been adjusted to accommodate for longer running times, i.e. the running time allowance on these sections are non-existent or even negative.

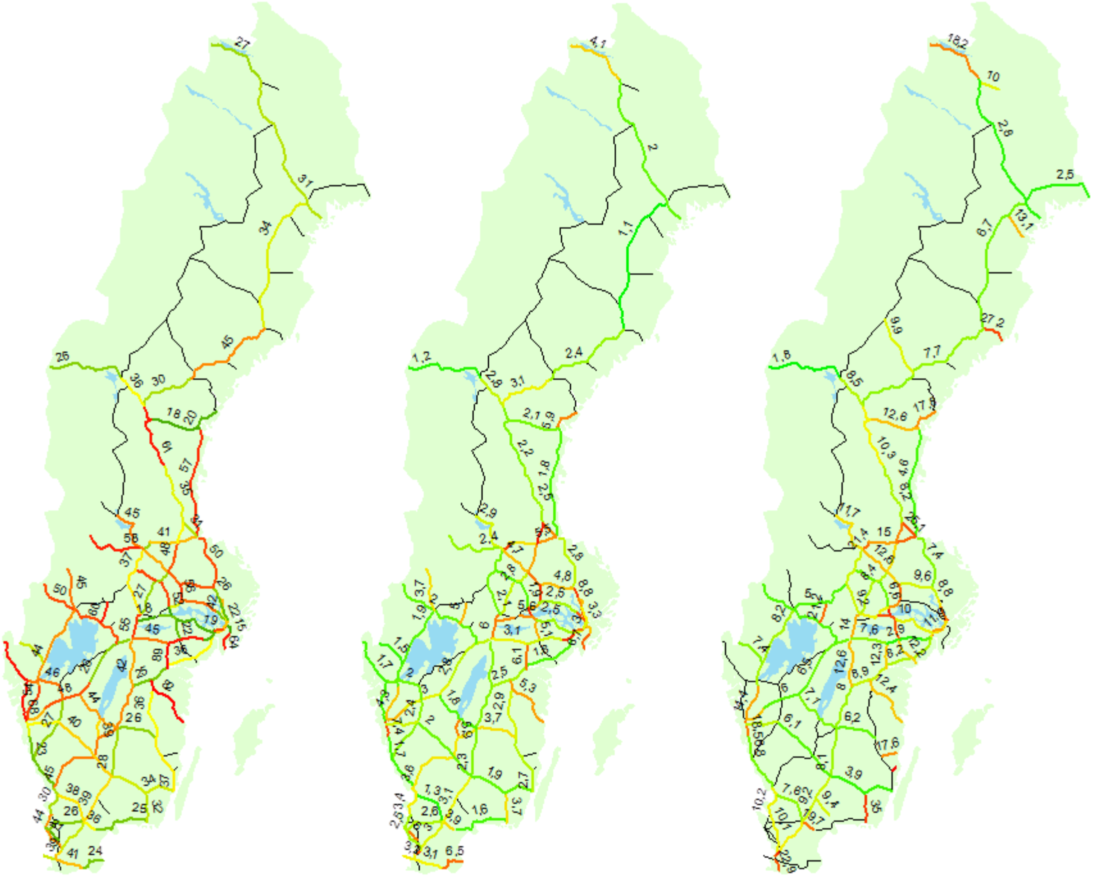


Figure 4.9: Left, proportion passenger trains with increased delay [%]. Middle, median of the increased delay for passenger trains [min/100km]. Right, median of the increased delay for freight trains [min/100km].

Delay data for CBA-analysis in RFC3

The measures which has been used in CBA-calculations is the share of delayed trains and the median of the increased delay in minutes/100km, the same as is showed on the maps in figure 4.9. In table 4.10 the values used for the actual lines is shown. Not that it is the delay in minutes for the delayed trains (26 % of passenger and 34 % of freight trains) and not the average delay. As all other trains are on time the average delay will be 0.55 minutes/100 km (35 sec) and 2.24 minutes/100 km for freight trains. Between Stockholm and Malmö the distance is 600 km and the average delay will be 6 times the delay/100 km, that means 3.3 minutes for passenger trains and 13.5 minutes for freight trains.

This measure is simple but made it possible to use both on short distance trains and on long distance trains. The possibility to be delayed is dependant of the line length.

The cancelled passenger trains was 1.7% in 2013 (Source: Trafikanalys 2017), but all cancellations was not because infrastructure failures, also vehicle and staff problems is a reason, so 1% can be a reasonable assumption.

For freight it was much higher but this is more a consequence of the production system where the freight companies want to have many slots for freight trains and cancel them if they cannot fill the freight trains. So 1% can also be a reasonable assumption for freight trains.

Table 4.10: Delays between Stockholm and Malmö (2013), Share of trains delayed more than one minute and the average delay for the delayed trains in minutes per 100 km and for the distance 600 km. Source: A. Lindfeldt, database (in PhD-Thesis).

		Passenger trains	Freight trains
Trains on time	share	74%	66%
Trains delayed > 1 minute	share	26%	34%
Median delay for delayed trains	minutes/100km	2,1	6,6
Median delay for all trains	minutes/100km	0,5	2,2
Stockholm-Malmö	km	600	600
Median delay for all trains	minutes	3,3	13,5

5 Parameters for line and train capacity in RFC3

5.1 Parameters for line capacity

The aim is to show the effects of the most important factors which are possible to put into a simulation model as train length, train weight, train speed, tractive effort, braking performance and signalling system. This can be applied in different ways: For all trains or more differentiated for trainload, wagonload and intermodal.

At first we have infrastructure and train performance. Train length and train weight are important factors which historically has been incremental changed to longer and heavier trains. Train weight is also dependant on the locomotives tractive effort. Today the TSI standard for train length is 750 m even if many lines have shorter and longer standards.

At 2030 we suggest to analyse 1,050 m as the longest train length. It is because it is the longest train which is possible to operate with one modern locomotive. An intermodal train with an average weight of 2 ton/meter will weight approx. 2,000 tonnes. From an operational point of view it is the most economical solution which gives the lowest cost. However there will also be a cost to adopt the infrastructure for longer trains. An alternative is to couple two 750 m trains to one 1,500 m train. For this there are also needs for some completing infrastructure investments.

To make it easier to operate long trains in 2030 we suggest that End of Train Device (EOT) will be implemented in this scenario. For 2050 we suggest 1,050 m train length in general and possibility to double the train length to 2,100m. This will be possible because we also suggest automatic couples and electric braking system for the 2050 scenario.

The train speed is important to maximize the number of trains per hour and also to harmonize speeds between freight and passengers trains. It is not only the shorter running time which is interesting but also that there will be less overtaking by passenger trains which take time and make trains dependant of each other with more delay risks. Many wagons and most locos are already today possible to run 120 km/h. However there is a need to harmonize braking rules in Europe which is an administrative problem.

The signalling system today is the existing depending of which line will be analysed. For 2030 we suggest to use ERTMS level 2, with shorter block lengths in critical sections. For 2050 we suggest ERTMS level 3 with continuous blocks between the trains.

The locomotives we suggest should be used in the trains today an engine with 300kN tractive effort and four axles with an axle load of 20 tonnes. For the future we suggest an incremental change in locomotive performance. In the 2030 we suggest an engine with 350kN tractive effort and four axles with an axle load of 22.5 tonnes. For 2050 we suggest an engine with 400kN tractive effort and four axles with an axle load of 25 tonnes. Trains will be operated manually by drivers as today and 2030 but for 2050 we suggest driverless operation with Automatic Train Operation (ATO), controlled by computers and dispatching centres.

For the wagons we suggest cast brakes today, LL-brakes 2030 and disc-brakes for 2050. According to trains above we assume, speed, braking systems and couples as described for trains.

Table 5.1: Parameters important for line capacity in RFC3.

Equipment	**Standard 2015**	**Scenario 2030**	**Scenario 2050**
Infrastructure and trains			
Max train lengths (m)			
Stockholm-Mjölby	630	750	1050
Örebro/Hallsberg-Mjölby	630	750	1050
Mjölby-Malmö	630	750	1050
Malmö-Copenhagen	630	835	1050
Copenhagen-Padborg	835	0	0
Padborg-Hamburg	835	0	0
Copenhagen-Puttgarden	0	835	1050
Puttgarden-Hamburg	0	835	1050
Oslo-Gothenburg	580	750	1050
Gothenburg-Malmö	630	750	1050
Max train weight (tonnes)	2 200	4 400	10 000
Max speed (km/h)			
Ordinary freight	100	100	120
Fast freight IM	100	120	160
Signalling systems	Different	ERTMS L2 in RFC	ERTMS L3 in RFC
Locomotives			
Tractive effort (kN)	300	350	400
Axle load (tonnes)	20,0	22,5	25,0
Axles	4	4	6
Max train weight	2 200	2 600	4 400
Axles	6	6	12
Max train weight	3 200	4 000	10 000
Duo-locos	Few duo-locos	Some duo-locos	All duo-locos
Drivers	Always drivers	Always drivers	All driverless ATO
Wagons			
Brake control	Pneumatic	Radio controlled EOT	Fully electronic
Brakes	Cast brakes	LL brakes	Disc brakes
Couplers	Screw couplers	Screw couplers	Automatic couplers
Max Speed	100 km/h	120 km/h	120-160 km/h

Table 5.2: Major infrastructure improvements in RFC3 in Sweden.

	Longer trains in Sweden	The Fehmarn Belt link completed 2027	Real high speed line completed in Sweden
Effects	Train lengths successive improved from 630 to 750 m and in long term possibly 1050 m	Distance Malmö-Hamburg shortened from 536 to 360 km Cost reduction -15% Transp time 8->5h-33%	Capacity on Southern Main Line for freight increase with 100% on day-time

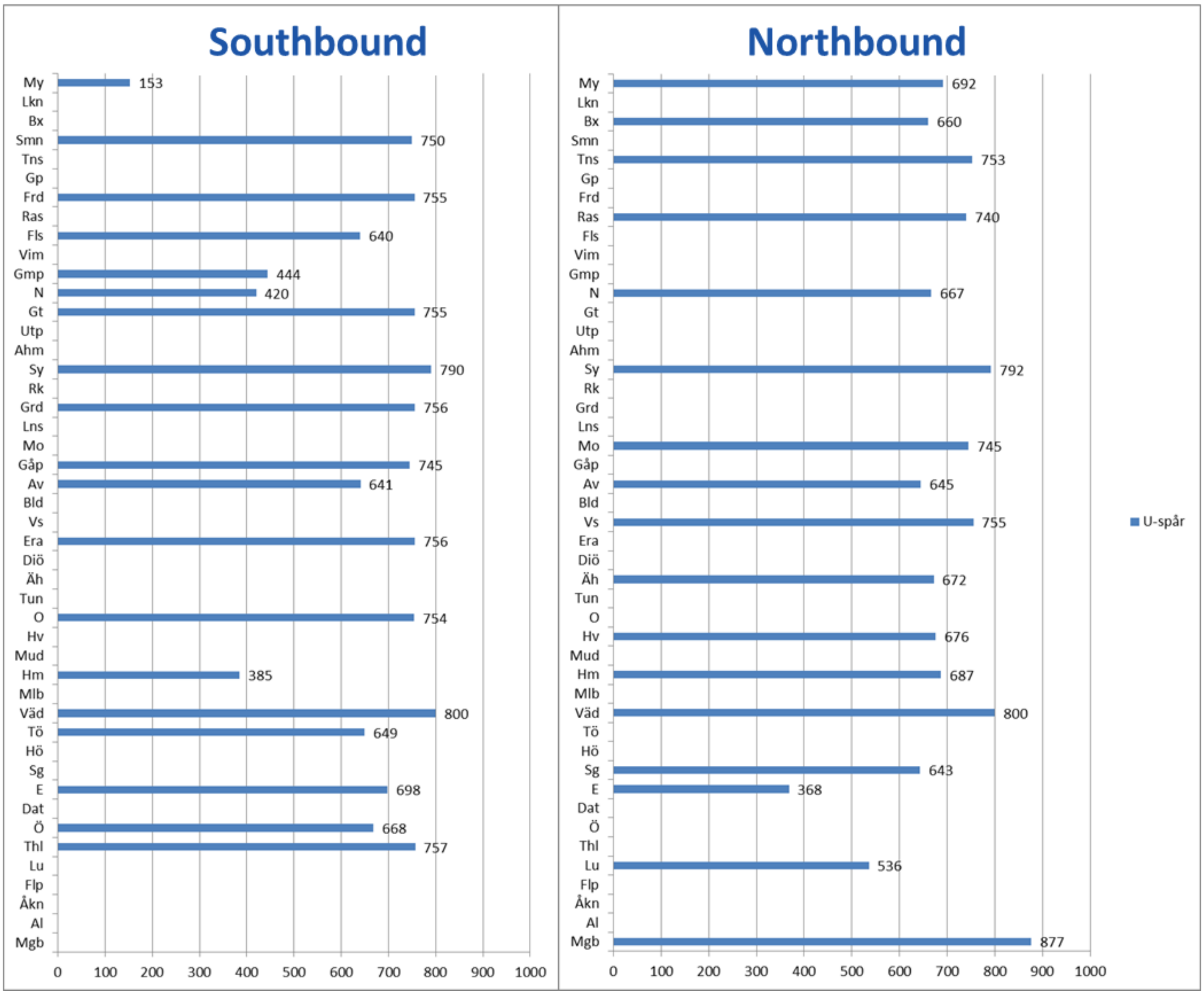


Figure 5.3: Length of passing tracks between Mjölby and Malmö. Source: Hans Boysen, KTH, 2014.

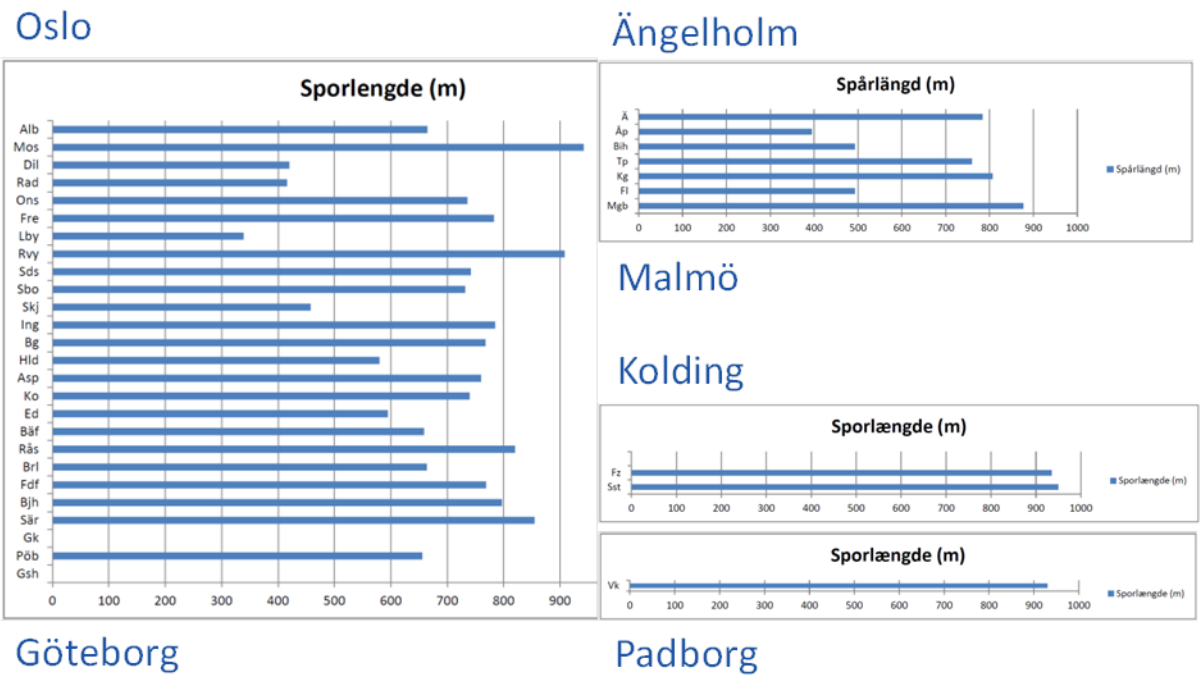


Figure 5.4: Length of crossing tracks between Oslo and Malmö. Source: Hans Boysen, KTH, 2014.

Analysis of double track operation with the TVEM-model

TVEM is a tool for infrastructure planning and timetable construction for double track lines with mixed traffic. The tool is well suited for evaluation of future operation since the infrastructure as well as the timetable is modelled as variables. TVEM is a feasible method as soon as the passenger traffic is known, or expected, to be operated according to a regular timetable. Different traffic patterns, i.e. frequencies, vehicles, speed levels, stopping patterns etc., and different combinations of patterns, may be systematically evaluated in TVEM (O. Lindfeldt 2010).

Real High Speed Lines are planned in Sweden therefore of special interest to show how the capacity for freight traffic would be affected by future high-speed lines. TVEM is a suitable method when the infrastructure is very well known and so the analysis could be concentrated on the timetable. TVEM automatically generates timetables that fulfil the requirements set for the passenger traffic (patterns) and evaluates each variant with regard to the number of possible freight trains. Different relative locations of passenger trains result in different number of freight trains.

In figure 5.5-5.8 three different scenarios for one of the busiest double track lines in Sweden, the Stockholm-Malmö line between Mjölby and Hässleholm analysed by the TVEM-model. The high-speed trains (red) are operated in 200 km/h regularly every hour and this limits the capacity for freight trains to two trains per hour. The first figure 5.5 shows the situation at 2008, the same structure as today. The model found 2,720 time table variants, this says something about the complexity in time table planning.

Figure 5.6 a situation with an upgraded double track with high speed trains in 250 km/h, some more overtaking stations and shorter four track sections. In this case the model found 86,700 time table variants. In this case the infrastructure investments could balance the greater speed differences but could not offer more slots for freight trains. The total capacity will on most sections be approximately the same as today, and the gain in journey times will not be of the same order as with dedicated high speed lines.

Finally figure 5.7 shows a situation where the high-speed trains are operated on a new line and the speed differences on the old line will be decreased. In this case the model found 4,700 time table variants. As can be seen in the graphical time table the traffic pattern is more simpler and the capacity for freight trains increase substantially in spite there still are one high speed train every second hour. The analysis clearly showed that a separation of fast and slow trains is the only alternative if both passenger and freight traffic are to be increased in the future.

The total effect on different sections of todays´ main lines is shown in figure 5.8. If dedicated high sped lines are built, most of the express trains can be removed from the Western and Southern main lines. In addition to extremely short travelling times and greater capacity and punctuality in passenger traffic, capacity is also freed up on the main lines for freight traffic and regional trains. Simulations with TVEM show that it is possible to operate 2-3 times more freight trains during the day. Freight trains that operate at night will not be affected so much.

The conclusion is that in the long term it is more socioeconomically profitable to build dedicated high-speed lines than to upgrade the conventional lines. The Swedish government has also decided to build the first part of the high-speed lines.

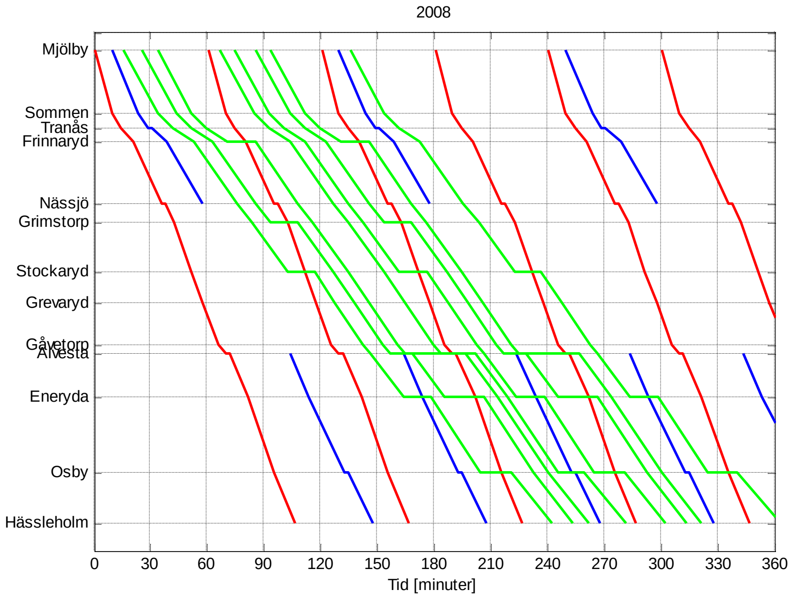


Figure 5.5: Example of a graphical timetable for double-track Stockholm-Malmö between Mjölby and Hässleholm in one direction with mixed freight and passenger traffic with maximum speed of 200 km/h. The red trains, X2000 Stockholm–Malmö, catch up the green freight trains that have to move aside and wait. The blue trains are regional trains that do not go all the way. In this example, 7 freight trains, 2 express trains and 2 regional trains in two hours can be accommodated, i.e. 5.5 trains per hour and direction.

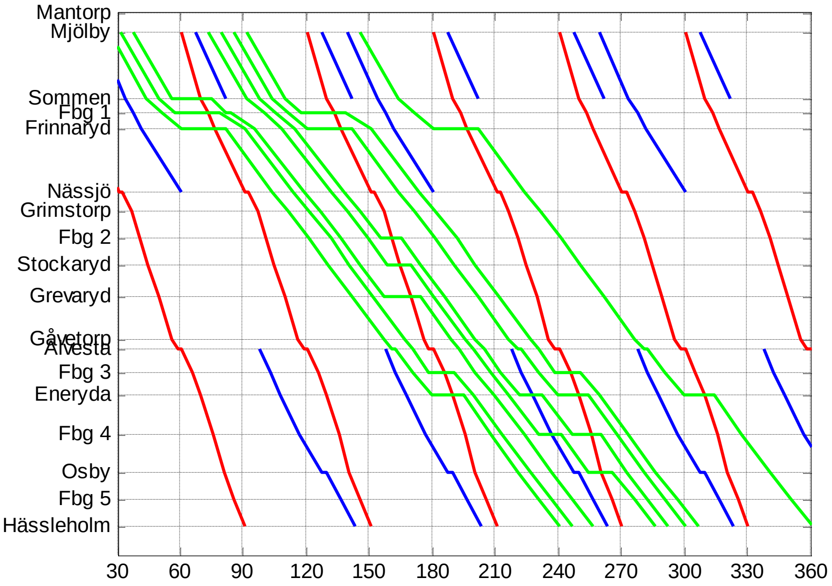


Figure 5.6: Example of a graphical timetable for double-track between Mjölby and Hässleholm in one direction with mixed freight and passenger traffic upgraded to with maximum speed of 250 km/h.

Some more overtaking stations has been built and a shorter four track section. By this it is possible to maintain the capacity in spite of larger speed differences with 7 freight trains, 2 express trains and 2 regional trains in two hours can be accommodated, i.e. 5.5 trains per hour and direction.

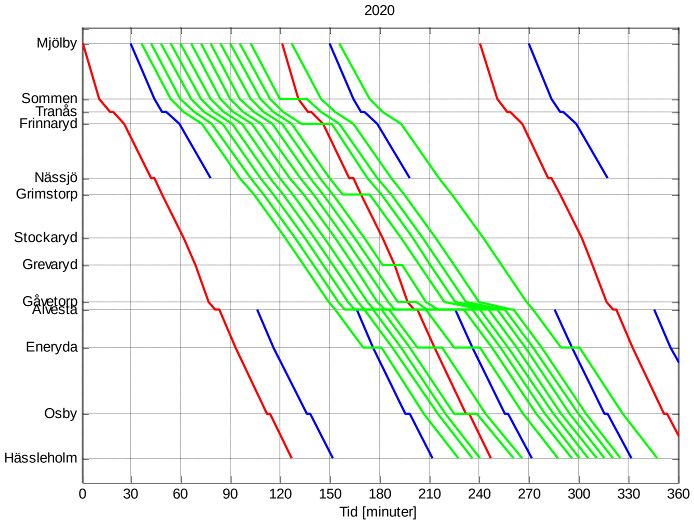


Figure 5.7: Example of a graphical timetable for double-track between Mjölby and Hässleholm in one direction with a separate high speed line built with maximum speed of 320 km/h. By this it is possible to increase the capacity on the old mainline to 12 freight trains, and still operate 2 regional trains and one high speed train in two hours i.e. 7.5 trains per hour and direction.

Figure 5.8: Number of possible train slots for freight trains during daytime on different double track sections on the mainlines Stockholm-Gothenburg/Malmö, at 2008 with maximum speed 200 km/h, with upgraded main lines to 250 km/h and with real high-speed lines built.

5.2 Parameters for train capacity

Some of the parameters in table 5.6 are important for train capacity. To make it relevant, it is necessary to split them in wagon load, intermodal container trains and inter modal trailer trains. There are many factors which influence how much freight it is possible to accommodate in a freight train beside the train length and the tractive effort it is i.e. the axle load, the tare weight, the loading length the train length utilization.

Suggestion for maximum parameters for scenario 2030 and 2050 for wagon load is shown in table 5.9. At first we have the maximum train length from the infrastructure parameters. If we assume the locomotive length we can calculate the available length for the wagon rake. If we assume a wagon length, in this case a 4-axle box car with slide doors, we can calculate the maximum number of wagons according to the train length which must be adjusted to an even number.

Then it is possible to calculate the maximum load weight per wagon by the axle load, the number of axles and the tare weight, here calculated by the tare weight per wagon metre which can be improved in the future. By this we can calculate a maximum train weight if all wagons are fully loaded as it often is in trainload operation in the loading direction.

In wagon load all wagons are not fully loaded so we can calculate a load factor which can be improved in the future. We can calculate an average payload per train and by adding the tare weight the average gross tonnes per train. We can also calculate some key performance indicators as the gross weight per train meter, the payload per train meter and the actual loading length per train meter.

It is also possible to calculate the volume capacity in m3 by taken the loading gauge into account. This has not been done here but is also possible to do. In practice a wagon load train have a mix of heavy freight and volume freight which to some extent is taken into account in the load factor. In real operation the trains are not loaded to the full length because there are variations in the actual demand depending of economic development and season variations. This has to be taken into account when we calculate the train capacity on a line and a corridor.

A calculation for a train load is shown in table 5.10.

In a similar way it is possible to calculate the capacity of intermodal trains. Here it is more important to calculate the length utilization and taken the available loading gauge into account. It is also necessary to taken into account the demand for longer containers from 40 to 45 ft and longer trailers which can be implemented in the future as well as more effective wagons.

In table 5.11 there are shown parameters for standard container trains and in table 5.12 there are shown parameters for standard trailer trains.

A summary of the effects on capacity for the different products is shown in table 5:13 and figure 5:14. It is possible to increase capacity rather much if both infrastructure and train parameters can be changed. Until 2030 by 30 % and to 2050 by at last 100 % for wagon load and intermodal and longer trains are the most important factor. For Train load it is possible to increase capacity more if the performance can be adopted to the customer needs on specific lines and heavier and longer trains in combination with higher axle load is the most important measures.

Table 5.9: Parameters important for train capacity for future wagon load trains in FC3.

Equipment		**Common standard 2015**	**Incremen-tal change 2030**	**System change 2050**
Infrastructure and trains				
Max train lengths in RFC	m	630	750	1 050
Double train length	m	NA	1 500	2 100
Locomotive length	m	18,9	18,9	18,9
Length of wagon rake	m	611	731	1031
Locomotives				
Axles	no	4	4	6
No of locomotives	no	1	1	1
Axle load	tonnes	21,0	22,5	25,0
Max speed	km/h	100	100	120
Max train weight	tonnes	2 200	2 600	4 400
Wagon load train				
Standard wagon load train				
Wagon type 2015		Habbins		
Wagon length	m	23,5	23,5	23,2
				Automatic couplers
Loading length	m	22,0	22,0	22,0
Length utlization	%	94%	94%	96%
Number of wagons	no	26,0	31,1	44,4
Number of wagons adjusted	no	26,0	31,0	44,0
Actual train length	m	630	747	1040
Axles/wagon	no	4	4	4
Axle load tonnes	tonnes	22,5	22,5	25,0
Max gross weight/wagon	tonnes	90	90	100
Tare weight per wagon	tonnes	26,5	25,9	24,4
Tare weight/wagonmeter	tonnes	1,13	1,10	1,05
Index		100	98	93
Load weight per wagon	tonnes	64	64	76
Index		100	101	119
Load weight/wagonmeter	tonnes	2,7	2,7	3,3
Index		100	101	121
Max train weight	tonnes	2 340	2 790	4 400
Train tare weight	tonnes	689	801	1 072
Max payload/train	tonnes	1 651	1 989	3 328
Load factor	%	50%	55%	60%
Average payload/train	tonnes	826	1 094	1 997
Train weight	tonnes	1 515	1 895	3 069
Gross weight/train metre	tonnes	2,4	2,5	3,0
Payload weight/train metre	tonnes	1,3	1,5	1,9
Loading length	m	572	682	968
Loading length/train length	%	91%	91%	92%

Table 5.10: Parameters important for train capacity for future train load trains in FC3.

Equipment		**Common standard 2015**	**Incremen-tal change 2030**	**System change 2050**
Infrastructure and trains				
Max train weight on line	tonnes	2 200	5 000	10 000
Train length	m			
Locomotive length	m	18,9	21,0	40,0
Length of wagon rake	m	324	600	971
Locomotives				
Axles	no	4	4	6
No of locomotives	no	1	2	2
Axle load	tonnes	21,0	22,5	25,0
Max speed	km/h	100	100	120
Max train weight	tonnes	2 200	5 200	8 800
Trainload				
Standard wagon load train				
Wagon type 2015		Shimms		
Wagon length	m	12,0	12,0	11,7
				Automatic couplers
Loading length	m	10,8	10,8	10,8
Length utlization	%	90%	90%	92%
Number of wagons	no	24,4	50,0	83,3
Number of wagons adjusted	no	27,0	50,0	83,0
Actual train length	m	343	621	1011
Axles/wagon	no	4	4	4
Axle load tonnes	tonnes	22,5	25,0	30,0
Max gross weight/wagon	tonnes	90	100	120
Tare weight per wagon	tonnes	20,0	21,0	19,9
Tare weight/wagonmeter	tonnes	1,67	1,75	1,70
Index		100	105	102
Load weight per wagon	tonnes	70	79	100
Index		100	113	143
Load weight/wagonmeter	tonnes	5,8	6,6	8,6
Index		100	113	147
Max train weight	tonnes	2 430	5 000	9 960
Train tare weight	tonnes	540	1 050	1 651
Max payload/train	tonnes	1 890	3 950	8 309
Load factor	%	50%	50%	50%
Average payload/train	tonnes	945	1 975	4 155
Train weight	tonnes	1 485	3 025	5 805
Gross weight/train metre	tonnes	4,3	4,9	5,7
Payload weight/train metre	tonnes	2,8	3,2	4,1
Loading length	m	292	540	896
Loading length/train length	%	85%	85%	85%

Table 5.11: Parameters important for train capacity for future IM container trains in FC3.

Equipment		**Common standard 2015**	**Incremental change 2030**	**System change 2050**
Infrastructure and trains				
Max train lengths in RFC	m	630	750	1 050
Double train	m	NA	1 500	2 100
Locomotive length	m	18,9	18,9	18,9
Length of wagon rake	m	611	731	1031
Locomotives				
Axles	no	4	4	6
No of locomotives	no	1	1	1
Axle load	tonnes	21,0	22,5	22,5
Max speed	km/h	100	120	120
Max train weight	tonnes	2 200	2 600	4 000
Intermodal container train				
Standard container train				
Wagon type 2015		Sggmrss		
Wagon length	m	29,6	29,3	29,0
Ct length	ft	45	45	45
Ct length	m	13,72	13,72	13,72
No of containers	no	2	2	2
Loading length	m	27,4	27,4	27,4
Length utilization	%	93%	94%	95%
Number of wagons	no	20,6	25,0	35,6
Number of wagons adjusted	no	20,0	24,0	35,0
Train length	m	611	722	1034
Axles/wagon	no	6	6	6
Axle load tonnes	tonnes	22,5	22,5	25,0
Max gross weight/wagon	tonnes	135	135	150
Tare weight per wagon	tonnes	27,3	26,4	24,9
Tare weight/wagonmeter	tonnes	0,92	0,90	0,86
Index		100	98	93
Load weight per wagon	tonnes	107,7	108,6	125,1
Index		100	101	116
Load weight/wagonmeter	tonnes	3,6	3,7	4,3
Index		100	102	119
Max train weight	tonnes	2 700	3 240	5 250
Train tare weight	tonnes	546	633	873
Max payload/train	tonnes	2 154	2 607	4 377
Average weight/container	tonnes	20	22	25
Load factor	%	37%	41%	40%
Average payload/train	tonnes	800	1 056	1 750
Train weight	tonnes	1 346	1 689	2 623
Gross weight/train metre	tonnes	2,2	2,3	2,5
Payload weight/train metre	tonnes	1,3	1,5	1,7
Loading length	m	549	658	960
Loading length/train length	%	90%	90%	90%

Table 5.12: Parameters important for train capacity for future IM trailer trains in FC3.

Equipment		**Common standard 2015**	**Incremen-tal change 2030**	**System change 2050**
Infrastructure and trains				
Max train lengths in RFC	m	630	750	1 050
Double train	m	NA	1 500	2 100
Locomotive length	m	18,9	18,9	18,9
Length of wagon rake	m	611	731	1031
Locomotives				
Axles	no	4	4	6
No of locomotives	no	1	1	1
Axle load	tonnes	21,0	22,5	22,5
Max speed	km/h	100	120	120
Max train weight	tonnes	2 200	2 600	4 000
Intermodal trailer train				
Standard trailer train				
Wagon type 2015		Sdggmrs		
Wagon length	m	34,2	34,0	33,5
Trailer		EU	EU	EU
Trailer length	m	13,60	13,60	13,60
No of trailers	no	2	2	2
Loading length	m	27,2	27,2	27,2
Length utilization	%	80%	80%	81%
Number of wagons	no	17,9	21,5	30,8
Number of wagons adjusted	no	17,0	21,0	30,0
Train length	m	600	733	1024
Axles/wagon	no	6	6	6
Axle load tonnes	tonnes	22,5	22,5	25,0
Max gross weight/wagon	tonnes	135	135	150
Tare weight per wagon	tonnes	35,0	26,7	25,8
Tare weight/wagonmeter	tonnes	1,02	0,98	0,95
Index		100	96	93
Load weight per wagon	tonnes	100	108	124
Index		100	108	124
Load weight/wagonmeter	tonnes	2,92	3,19	3,71
Index		100	109	127
Max train weight	tonnes	2 295	2 835	4 500
Train tare weight	tonnes	595	560	775
Max payload/train	tonnes	1 700	2 275	3 725
Average weight/trailer	tonnes	27	28	30
Load factor	%	54%	52%	48%
Average payload/train	tonnes	918	1 176	1 800
Train weight	tonnes	1 513	1 736	2 575
Gross weight/train metre	tonnes	2,5	2,4	2,5
Payload weight/train metre	tonnes	1,5	1,6	1,8
Loading length	m	462	571	816
Loading length/train length	%	77%	77%	77%

Table 5.13: Summary of effects of changes in capacity in scenarios for 2030/2050.

Freight train capacity	Scenario 2015	2030	2050
Av. Payload/train			
Wagon load	826	1 094	1 997
Trainload on specific lines	945	1 975	4 155
IM container	800	1 056	1 750
IM trailer	918	1 176	1 800
Average train	863	1 353	2 526
Train mix			
Wagon load	30%	25%	20%
Trainload	30%	30%	30%
IM container	30%	35%	40%
IM trailer	10%	10%	10%
Total	100%	100%	100%
Increase			
Wagon load	0%	32%	142%
Trainload on specific lines	0%	109%	340%
IM container	0%	32%	119%
IM trailer	0%	28%	96%
Average train	0%	57%	193%

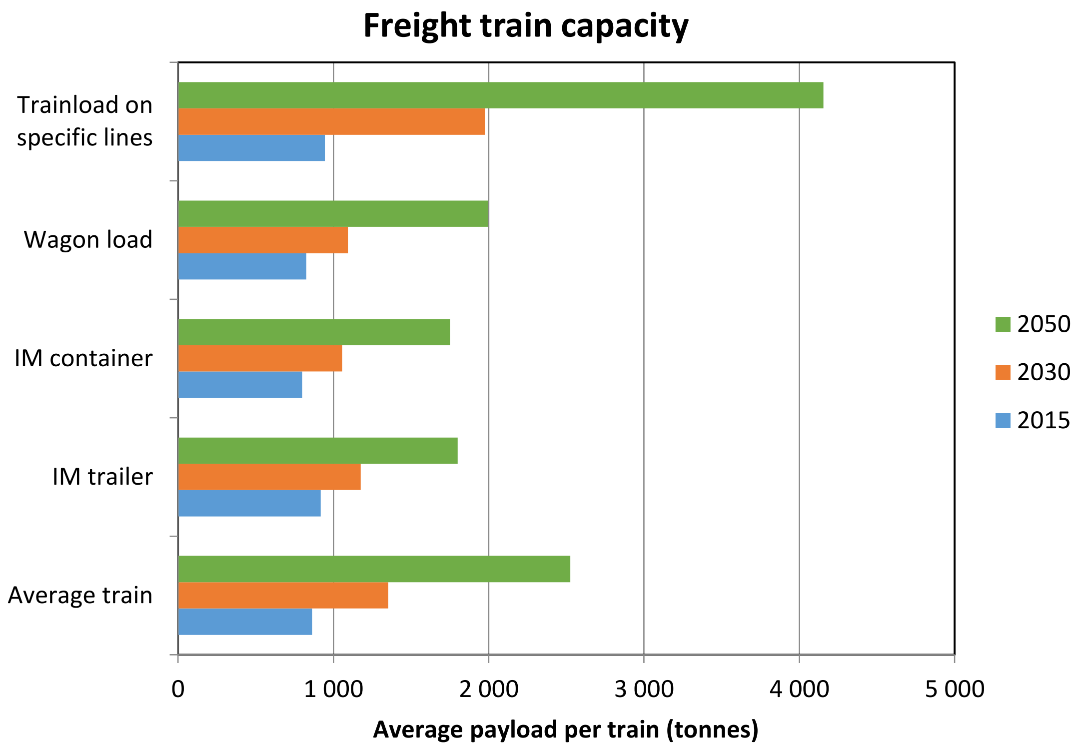


Figure 5.14: Summary of effects of changes in capacity in scenarios for 2030/2050.

6 KTH cost models for economic evaluations

The KTH cost model is a more general cost model in which different production systems can be calculated. In the VEL-wagon project the model has been completed with a wagon costs-model in which different wagon types can be tested, both existing and hypothetical.

6.1 The train cost model

KTH has developed a cost model to make our own calculations for different wagon types. The aim was to construct a flexible model which can be used for calculations for different wagon types in different countries. The purpose is to specify the most significant costs, therefore the model is not very detailed.

The model consists of a train operating model and a wagon specification model. The structure of the train operating model is shown in Table 6.1 and that of the wagon specification model is shown in Table 6.2.

The train operating model consists of transport specification and train specification data from which data for the cost calculation is processed i.e. yearly production per locomotive and wagon, number of train kilometres, wagon kilometres and gross tonne kilometres per trip. Several parameters are possible to change, including the distance of operation, time table time and supplement for shunting, number of locomotives, number of wagons, load factor and empty run factor.

The aim is to calculate all costs for the locomotive itself that means also the pure cost for the train if it were operating without wagons. That means that not only the locomotive capital cost, its maintenance cost and the cost for the engineer but also the energy cost and the track access costs for the locomotive are allocated to the locomotive. To the wagons apart from their capital and maintenance cost the marginal cost for energy and track access according to the gross tonne kilometres of the wagons including payload are allocated. There is also an amount for insurance per wagon according to the investment cost.

Finally there is also an overhead for administration, planning and risk. This is calculated as a ~~%~~ percentage of the total operating and capital costs.

It is possible to change all costs according to actual costs in different countries i.e. track charge~~s~~ costs depending on cost structure in train kilometres and gross tonne kilometres. The basic model has been developed for Swedish conditions at the year 2011. However, the model has been calibrated to the NEA calculations for the Rotterdam-Lugano intermodal train. Today the models calculate in SEK (Swedish crowns) and € but the currency is possible to change. Costs has then been updated to the actual year when the model has been used.

In the wagon specification model the most important features of a freight wagon can be implemented. There is also a rough model to calculate the investment costs and the maintenance costs according to the components of the wagon. Therefore it is possible to construct a hypothetical wagon with bogies or single axles, different frames and equipment. There are also possibilities to make calculations of payload depending on axle load, number of TEU depending of loading length and other measures which are important to the economy.

Table 6.1: Cost model for train operation

Specification	Variable	Cost
Transport data		
Running distance	km	
Scheduled transit time	h:min	
Supplement for shunting	% of timetabltime	
Trips per year	number	
Train data		
Number of locos	number	
Number of wagons	number	
Tractive power/loco	KW	
Weight/loco	tonnes	
Length/loco	m	
Length/wagon	m	
Tare weight/wagon	tonnes	
Max load/wagon	tonnes	
Load factor	%	
Empty run factor	%	
Cost for locomotive		
Engineer	timetabletime	Cost/hour
Maintenance locomotive	locokm	Cost/km
Energy for locomotive	KWh/locokm	Cost/KWh
Track fees for locomotive	trainkm	Cost/trainkm
Capital cost	Investment cost	Depritiation/year
		Average Interest/year
	Yearly operation	Cost/locokm
Cost for wagons		
Maintenance for wagons	wagonkm	Cost/wagonkm
Energy for wagons	KWh/grosstonkm	Cost/KWh
Track fees for wagons	grosstonkm	Cost/grosstonkm
Insurance	Investment cost	% of investment cost
Capital cost	Investment cost	Depritiation/year
		Average Interest/year
	Yearly operation	Cost/wagonkm
Overhead		
Adm and planning	% of total cost for	Operation and capital
Risk/profit	% of total cost for	Operation and capital
Total cost		
Cost for locomotive	Summarized	All costs for locos
Cost for wagons	Summarized	All costs for wagons
Overhead	Summarized	All overhead costs

6.2 The wagon cost model

The prices for buying existing wagons are relatively well-known by the industry even if it is of course depending of the number of wagons, actual currency and so on. The cost for building a wagon with different components is not so well known.

Because we couldn´t find any cost models for building wagons we decided to take a first step to develop a model. The model has been used in combination with a model for train operating costs.

The aim has been to develop a cost model which can be used for calculating cost, weight and payload for existing wagons as well as hypothetic future wagons.

Method

The wagon has been spitted up in parts which usually are manufactured separate and put together. The cost and weight of the components has been estimated by Tatravagonka. A very simple model for calculating maintenance costs according to investment costs has been developed.

In the model for analysis of construction cost, maintenance cost and mass breakdown the wagons has been split up in the following components:

- Underframe (cost per m and total cost)
- Bogies or running gear with suspension
- Axles
- Brake gear
- Buffers and couplers
- Other equipment
- Loading equipment

Delimitations

The model has been used to evaluate the efficiency of the VEL Wagon in comparison to other modern container wagons of various configurations. The model for calculating maintenance costs and energy consumption are very simplified and is intended to be developed further in the future.

Description of the model

The model is shown in Table 6.2.

Table 6.2: Example of specification of the wagon-cost-model

Type	SEK/Euro	Sgns	Sggrss	Metrans	VEL-IM	VEL-IM	VEL-IM
	9,50	60ft	80ft	80ft (VEL)	80ft	90ft	90ft 25t
Wagon specification							
Axles/wagon		4	6	4	4	4	4
Bogies/wagon		2	3	2	2	2	2
Axle load	tonnes	22,5	22,5	22,5	22,5	22,5	25,0
Max gross weight/wagon	tonnes	90,0	135,0	90,0	90,0	90,0	100,0
Tare weight/wagon	tonnes	19,0	27,5	21,5	23,1	24,7	25,6
Payload capacity/wagon	tonnes	71,0	107,5	68,5	66,9	65,3	74,4
Load volume	m3						
Number of TEUs per wagon	number	3	4	4	4	4	4
Nominal loading length	feet	60	80	80	80	90	90
Loading length calculated	0,3125	18,8	25,0	25,0	25,0	28,1	28,1
Total loading length	m	18,5	25,2	24,7	24,7	28,0	28,0
Length over buffers	1,24	19,7	26,4	25,94	25,9	29,2	29,2
Energy consumption	kWh/grosstonnekm	0,0152	0,0152	0,0140	0,0140	0,0141	0,0142
Maintenance cost	€/km	0,0152	0,0233	0,0156	0,0163	0,0165	0,0183
Investment cost	€ thousands	73	113	75	92	94	102
Maintenance cost	SEK/km	0,14	0,22	0,15	0,16	0,16	0,17
Investment cost	1000 SEK	692	1 071	716	877	891	967
		1,00	1,55	1,03	1,27	1,29	1,40
Construction cost (€)							
Underframe		25 769	41 880	26 573	33 216	34 545	34 545
Bogie frames and suspension		30 000	45 000	30 000	30 000	30 000	34 500
Wheelsets		8 800	13 200	8 800	8 800	8 800	10 120
Brake gear		6 005	11 325	7 401	7 401	7 401	8 511
Buffers and couplers		1 760	1 616	1 880	1 880	1 880	2 162
Other equipment		757	792	441	441	441	507
Loading equipment		1 910	1 887	2 205	2 205	2 205	2 205
Sum		66 200	102 500	68 500	83 943	85 272	92 550
Incl others	10%	72 820	112 750	75 350	92 337	93 799	101 805
Maintenance cost (€/km)	‰ of investment cost						
Underframe	0,00010	0,0026	0,0042	0,0027	0,0033	0,0035	0,0035
Running gear with brakes	0,00025	0,0112	0,0174	0,0116	0,0116	0,0116	0,0133
Other equipment	0,00015	0,0007	0,0006	0,0007	0,0007	0,0007	0,0007
Sum		0,0144	0,0222	0,0149	0,0156	0,0157	0,0175
Incl others	5%	0,0152	0,0233	0,0156	0,0163	0,0165	0,0183
Maintenance cost (€/km)	‰						
Underframe	0,00010	0,0026	0,0042	0,0027	0,0033	0,0035	0,0035
Bogie frames and suspension	0,00025	0,0075	0,0113	0,0075	0,0075	0,0075	0,0086
Wheelsets	0,00025	0,0022	0,0033	0,0022	0,0022	0,0022	0,0025
Brake gear	0,00025	0,0015	0,0028	0,0019	0,0019	0,0019	0,0021
Buffers and couplers	0,00015	0,0003	0,0002	0,0003	0,0003	0,0003	0,0003
Other equipment	0,00015	0,0001	0,0001	0,0001	0,0001	0,0001	0,0001
Loading equipment	0,00015	0,0003	0,0003	0,0003	0,0003	0,0003	0,0003
Sum		0,0144	0,0222	0,0149	0,0156	0,0157	0,0175
Incl others	5%	0,0152	0,0233	0,0156	0,0163	0,0165	0,0183
Mass (kg)							
Underframe		8 172	11 705	10 427	12 488	13 977	13 977
Bogie frames and suspension		3 928	5 892	3 920	3 674	3 674	4 148
Wheelsets		4 872	7 308	5 080	5 008	5 008	5 452
Brake gear		746	1 266	610	600	700	700
Buffers and couplers		560	538	588	580	580	580
Other equipment		142	197	92	92	92	92
Loading equipment		580	594	783	660	670	670
Sum		19 000	27 500	21 500	23 102	24 701	25 619

6.3 Cost for operating VEL-Wagon compared with other wagons

The cost for using the VEL wagon in a train has been compared with other wagons available on the market:

- 60 ft 4 axles wagon Sgns/ss
- 80 ft 6 axles wagon Sgrs/ss
- 80 ft 4-axles VEL wagon (Sggns/ss)
- 40 ft two-axles wagons Lgns/ss
- 45 ft two-axles wagons Lgns/ss

There are several options to calculate the transportation cost. It can be calculated as the cost per TEU in trains with equivalent capacity, the cost depending on variable capacity in TEU and the cost per TEU with variable train length. Evaluation can also be made of the cost structure of the total cost of the train so it is for example possible to examine the costs of the wagons as a share of the overall cost of the train.

The first figures shown here are for a 900 km intermodal train in Sweden. The cost has been calculated per TEU in a train with an equivalent capacity of 80 TEU and 80% load factor for VEL wagons and if possible the same or almost the same numbers with other wagons.

As can be seen in Figure 6.3, VEL wagon is more efficient than the 60 ft 4-axle~~s~~ wagon Sgns as well as the 80 ft articulated 6-axle~~s~~ wagon Sgrs. The transport cost/TEU is 5% lower than for Sgns and 9% lower than for Sgrs. The 80 ft Sgrs has the advantage of more flexible loading of 20 ft and 40 ft containers than the 60 ft Sgns but this advantage has also VEL wagon.

The two-axles 40 ft wagon gives the same transport cost per TEU as the VEL wagon but have has the disadvantage of limited payload, which means that many containers cannot be load on this wagon. The same is the situation of the 45 ft two-axle wagon. Although the ISO standard for 40 ft containers limits gross mass to 30.5 tonnes, this is a minimum limit, and there are 40 ft and 45 ft containers at up to 39 tonnes gross mass.

In figure 6.4 also the cist/TEU depending on the loading scheme, the mix of 20 and 40 ft containers. Also here VEL-wagon gives the lowest cost because it has the longest floor on which it is possible to place different combinations of containers. However, if 45 ft containers will be more common, the existing VEL-wagon is not so efficient because it is only possible to load one 45 ft container/wagon.

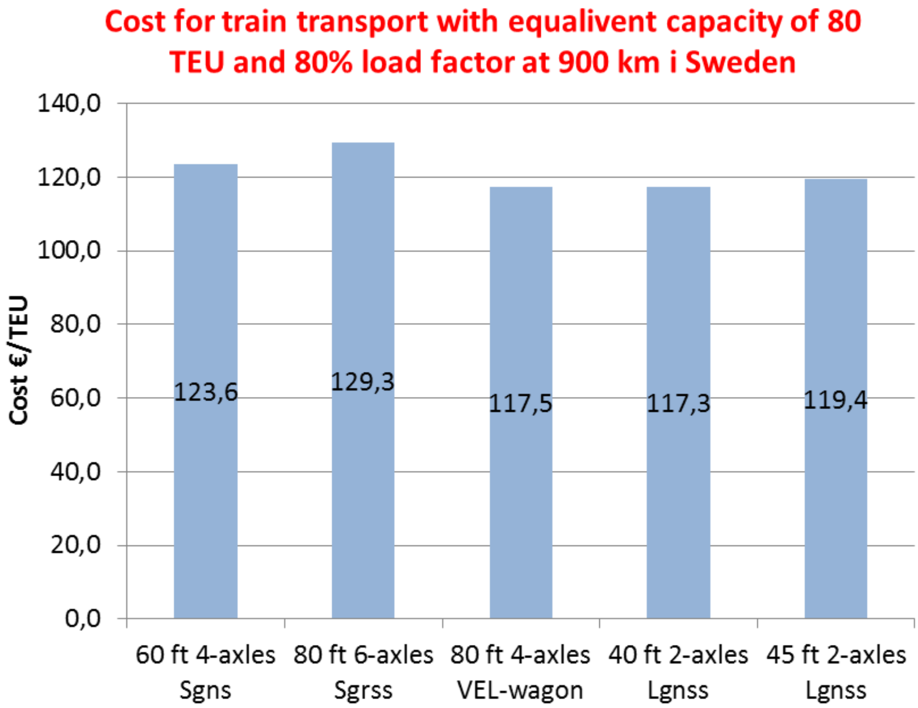


Figure 6.3: Cost in€/TEU for a train with capacity of 80 TEUs, 80% load factor and 900 km running distance

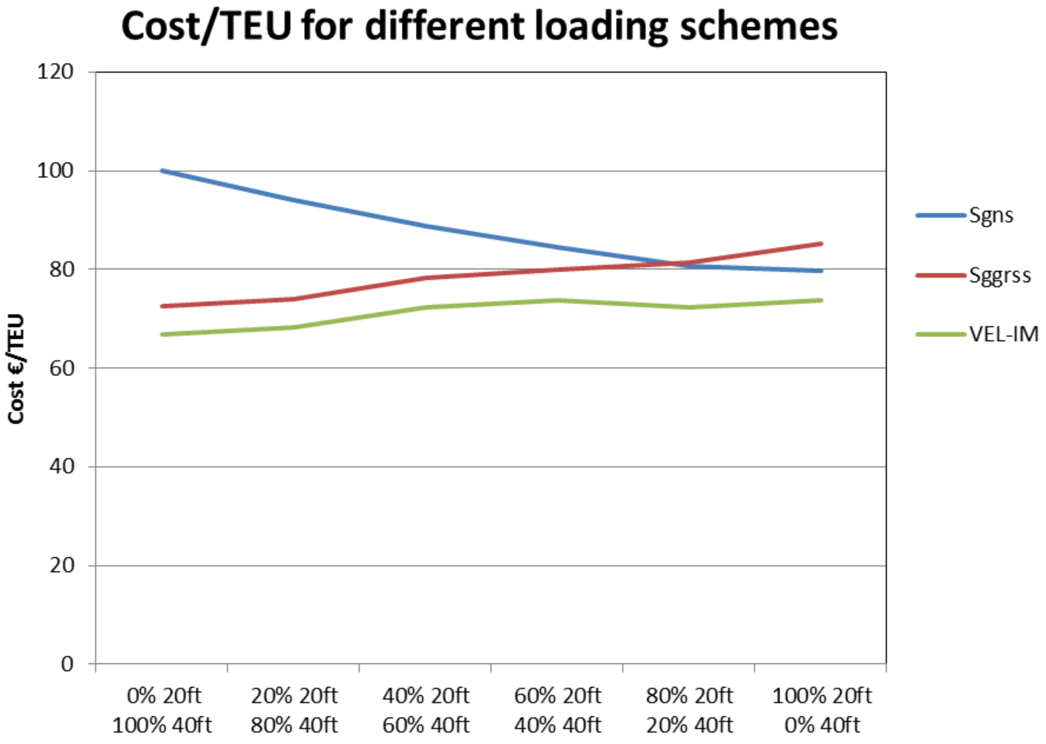


Figure 6.4: Transport cost per TEU for an intermodal train with different-wagons and loading schemes with 80% load factor at 600 km in Sweden.

6.4 Cost for transports in different countries

The cost for intermodal transport chains with VEL-wagon and conventional wagons will be calculated and compared with direct truck transports. Break-even point between intermodal and truck will be calculated for different cases in Sweden and Germany. The cost per TEU will be calculated for a standard train in Sweden and Germany for different wagon types. Maximum train length is 600 m and maximum train weight 1,800 ton with electric traction.

A simplified comparison has been made between Sweden and Germany. The cost that has been taken into account is different track access charges, energy prices and engineer costs. The calculations have been done for a 600 km running distance with a train consisting of 20 VEL wagons and with a load-factor of 80%. The results are shown in Figures 6.5 to 6.6

In Figure 6.5 it is shown that the cost for track access is much higher in Germany than in Sweden – 20% share of the total costs in Germany compared with 7% share of the total costs in Sweden. On the contrary the cost for the engineer is 14% in Sweden and 7% in Germany. Also the cost for energy is higher in Germany than in Sweden. The other differences in cost-shares in Germany compared with Sweden and the fact that the higher share for track access and energy in Germany will affect the shares. The absolute cost for locomotives and wagons are the same in the calculation.

The costs allocated to locomotives and wagons are shown in Figure 6.6. Here the cost-share for the locomotive is higher because the track access charges are calculated according to the train-kilometres and this has been allocated to the locomotive. Therefore the cost-share for the wagons is lower. This means that a more efficient wagon such as the VEL wagon is more important in Sweden than in Germany. In Sweden the track access charges are more affected by the gross tonne-kilometres than the train-kilometres. So even if the energy-cost, which has been allocated according to the gross tonne-kilometres for the locomotives and the wagons, respectively, is higher in Germany than in Sweden, this is less important than the relatively higher track access charges.

Finally, the total transport cost per TEU is shown in Figure 6.7. The total cost is 19% lower in Sweden than in Germany. The cost differences between different wagons are slightly larger in Sweden than in Germany. But the savings of using the VEL wagon instead of a 80 ft articulated 6-axle~~s~~ Sgrs-wagon is 9.5% in Sweden and 8.5% in Germany so the difference~~s~~ is not so great. It is still evident that the VEL wagon is an effective wagon concept despite differences in cost structure between nations.

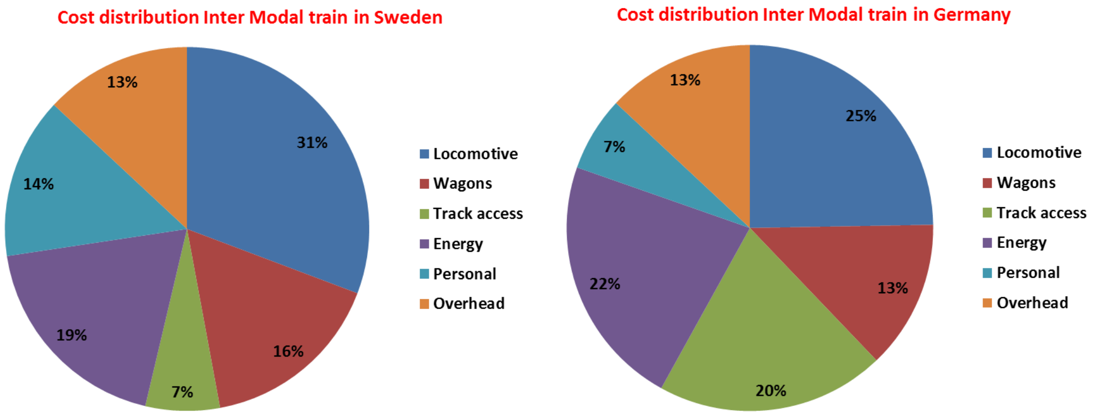


Figure 6.5: Cost structure for an intermodal train in Sweden and Germany. Distance 600 km, train with 20 VEL wagons with a capacity of 80 TEUs and a load factor of 80%.

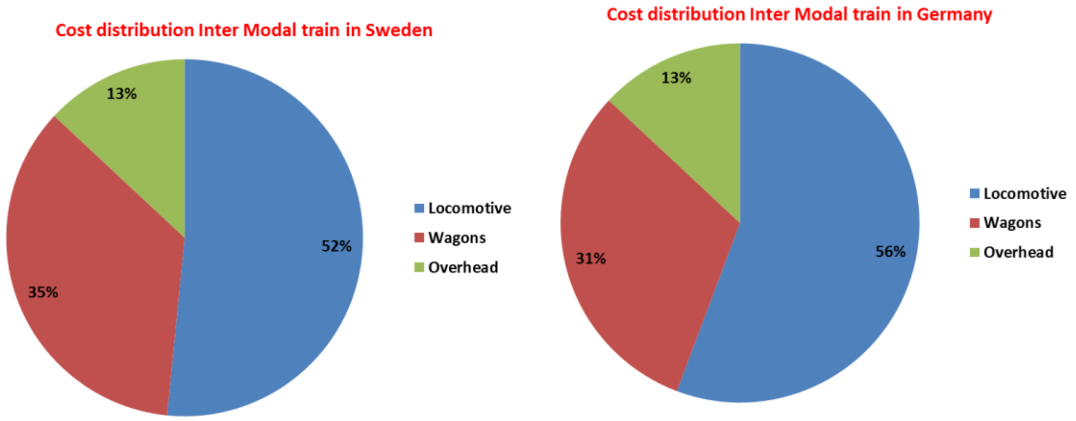


Figure 6.6: Cost distribution between locomotive, wagons and overhead for an intermodal train in Sweden and Germany. Distance 600 km, train with 20 VEL wagons with a capacity of 80 TEUs and a load factor of 80%.

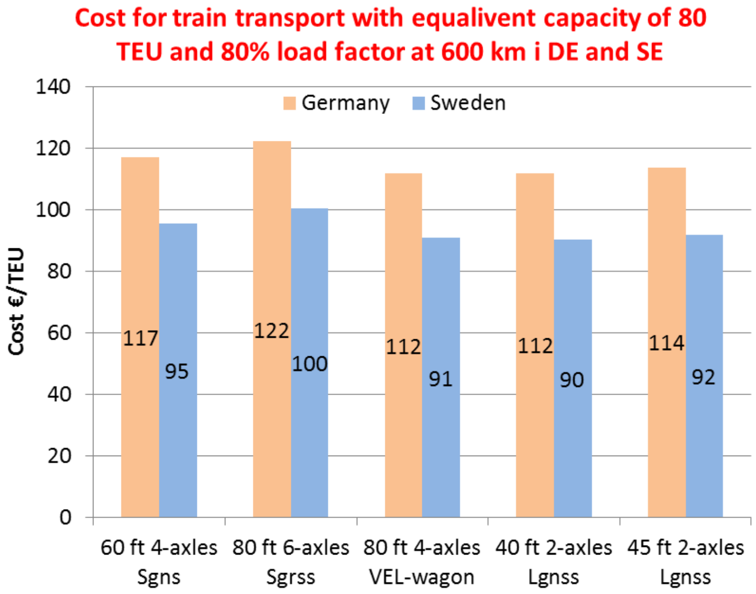


Figure 6.7: Transport cost per TEU for an intermodal train in Sweden and in Germany. Running distance 600 km, train with 20 VEL wagons with a capacity of 80 TEUs and a load factor of 80%.

6.5 Cost for inter modal transport chains compared with direct trucking

The cost per TEU with the standard train and the three different wagons including terminal handling and feeder transports will be calculated for:

- Sweden 25,25 m truck and 32 m experiment DuO2 truck
- Germany 18 m truck and 25,25m Mega truck
- European 18 m truck

Calculation has been done for typical intermodal transport chains incl. terminal handling and feeder transport. The result is shown by diagrams with cost according to distance at 0-1000 km. Distance is important of two reasons:

1. There is a rank-size-rule about transport distances and transport volume that means that the shorter distance the bigger volumes in tonnes are available on the market.
2. It is also possible to identify the break-even-point according to distance compared with direct trucking or other modes.

By this it is also possible to analyze the consequences of more efficient wagons and trains as well as more efficient trucks on the competition and cooperation between the modes.

The total market in tons for different distances in Sweden is shown in figure 6.8 and the increase of the volumes from 1987-2008. On the distance 300-400 km there are approximately 4 times as much tonnes on the market as on the distance 600-700 km. So the distance when inter-modal is competitive is important to get enough volumes to fill the trains and get a sufficient frequency.

Figure 6.9 shows the market share between rail and truck in Sweden and the change 1987-2008. The truck has gained market share about 10 percent units on many distances except on the interval 900-1000 km. One reason for that the gross weight for trucks in Sweden was increased from 51.4 to 60 tonnes around 1990 and the payload increased form approx. 30 to 40 tonnes. That means that the cost for transporting heavy goods by truck decreased by approximately 20% and because customers are price sensitive they in some cases choice truck instead of rail.

In figure 6.10 the transport cost per ton for an inter-modal transport chain according to distance compared with a 25,25 m truck in Sweden is shown. It is a train with average loaded 20 ft containers on the different wagons analyzed in this report: Sgns, Sgrss, Lgns and VEL-wagon. In this case all wagons are loaded to its full capacity and the differences in total transport cost are not very great but in the order of as most 5% on medium distances. The

VEL-wagon in itself can increase the available market by reducing the break-even-point for inter-modal from 550 km to 500 km compared with transport with the wagon type Sgns/Sgrss.

In figure 6.11 the same calculations has been done for a train with swap-bodies loaded containers on the different wagons. In this case the differences will be more important because it is possible to load three swap-bodies on VEL-wagon but only two on Sgns and Sgrss. As can be seen the differences in total transport cost are in the order of 10% on medium distances. The VEL-wagon in itself can increase the available market by reducing the break-even-point for inter-modal from 550 km to 420 km compared with the most costly transport with the wagon type Sgrss or in an order of 15%.

In figure 6.12 calculations has been done for a train with maximum payload loaded in unit loads on the different wagons. This case is not in favour of VEL-wagon because the weight of 80 ft load is distributed on only four axles. The differences are small but here the 6-axles Sgrss is best with 107 ton payload. But here can the feeder transport by truck be a restriction, a 20ft unit load of approximately 26 tonnes gross weight is possible to load on a truck but not two or more. This is more like a wagon-load system there unit loads go direct to the industry.

Figure 6.13 shows the transport cost per ton for an inter-modal transport chain with 20 ft containers compared with a 25.25 m truck and a 32 m experimental truck in Sweden. The 32 m truck has possibility to load 4 TEU instead of 3 as the 25,25 m truck which make it much more efficient. The longer truck will push break-even-point for inter-modal with VEL-wagon from approximately 500 km to 600 km. The VEL-wagon in itself can increase the available market by reducing the break-even-point for inter-modal from 550 km to 500 km compared with transport with the normal wagon types. So in this case a longer freight wagon is not enough to compete with a longer truck. This is because of the relative high fixed costs for inter-modal transports for terminal handling and feeder transports.

Figure 6.14 shows the transport cost per ton for an inter-modal transport chain with 20 ft containers compared with an 18 m EU-truck and a 25.25 m Swedish truck calculated with Swedish costs. The 25.25 m truck has possibility to load 3 TEU instead of 2 as the 18 m truck which make it much more efficient. This is more like the situation in Europe if Megatrucks will be allowed instead of ordinary EU-trucks. In this case the longer truck will push break-even-point for inter-modal from approximately 400 km to 500 km. The effect of more efficient freight wagons is approximately - 50km this case.

However, the situation is not exactly the same in Europe as in Sweden. For example in Germany there are road fees and track access charges are higher. It also is a question of weight and not only length of the trucks, so in reality the situation is more complex.

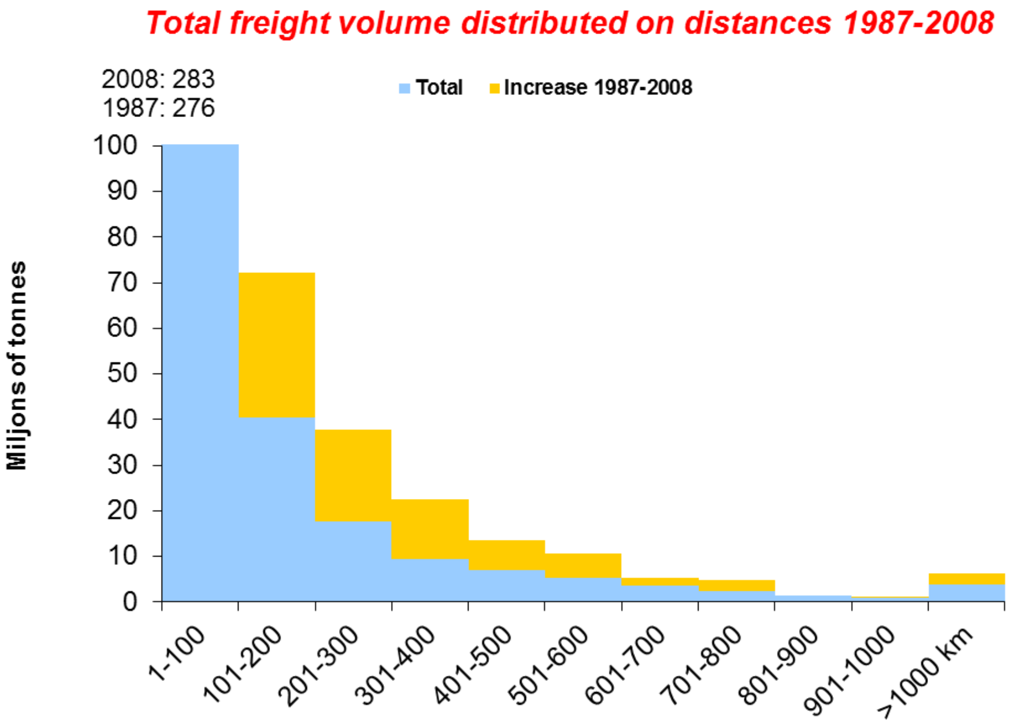


Figure 6.8: Rank-size-rule for transport volumes in Sweden 1987-2008. Source: Jakob Wajsman, Trafikverket.

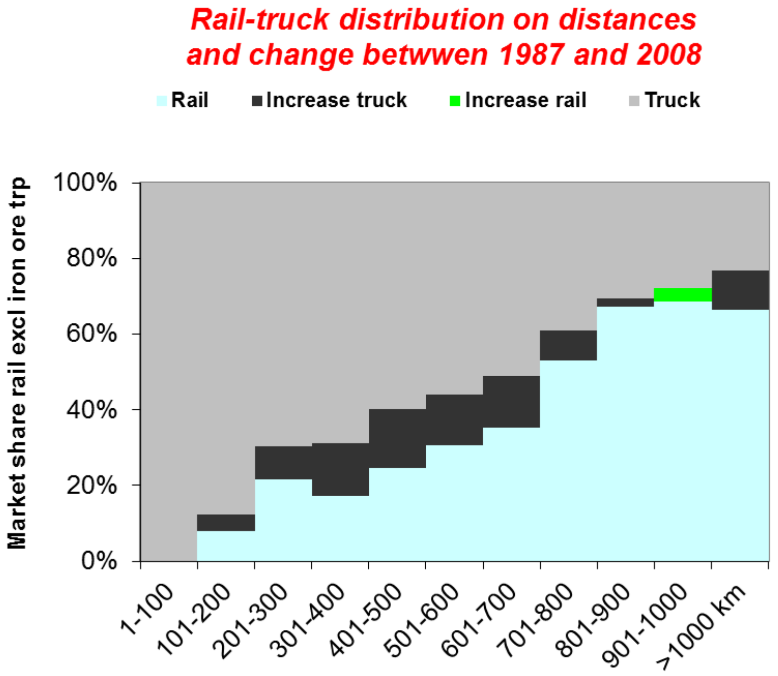


Figure 6.9: Market share for rail-truck in Sweden and change in market share 1987-2008. Source: Jakob Wajsman, Trafikverket.

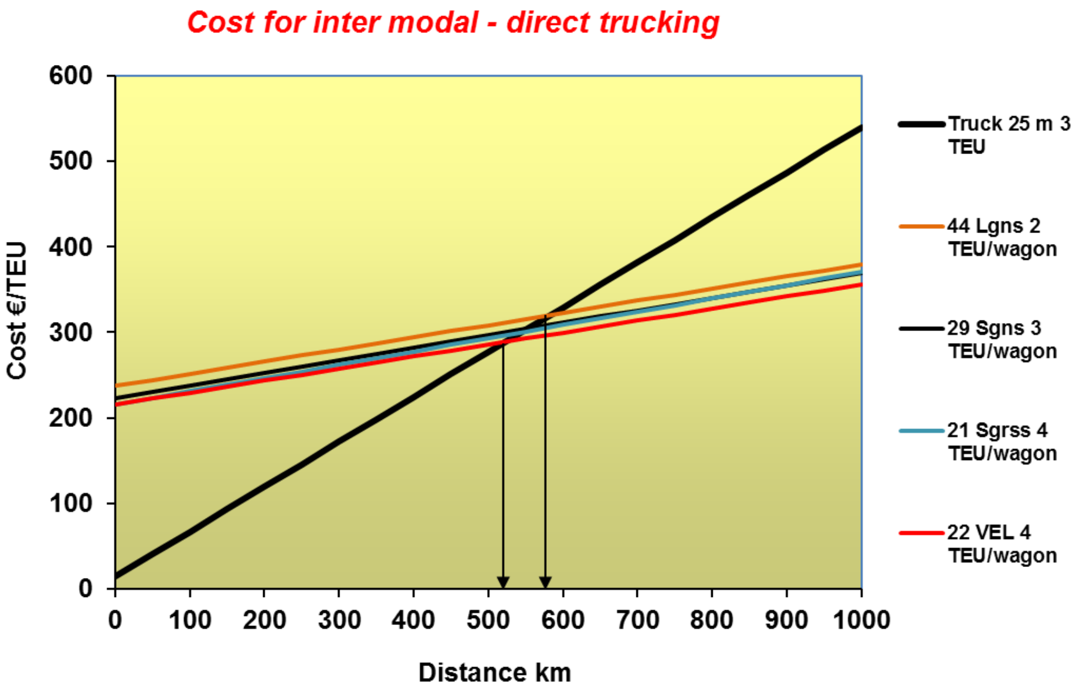


Figure 6.10: Transport cost per ton for an intermodal transport with containers on different wagons in Sweden compared with a 25.25 m truck.

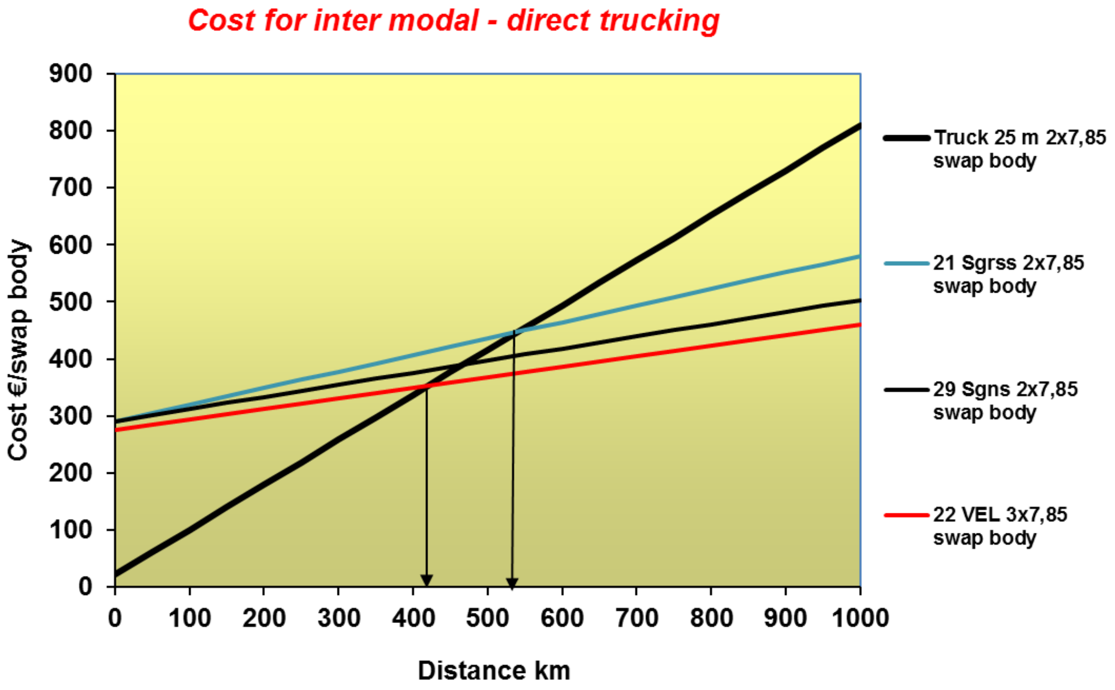


Figure 6.11: Transport cost per ton for an intermodal transport with swap-bodies on different wagons in Sweden compared with a 25.25 m truck

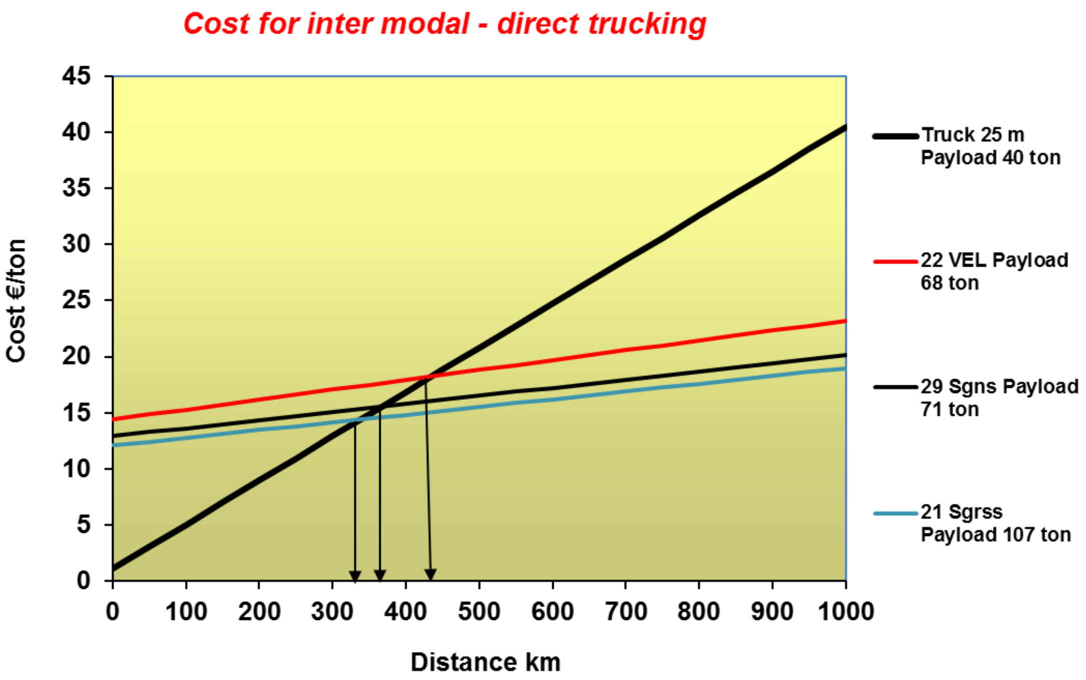


Figure 6.12: Transport cost per ton for an intermodal transport with maximum payload in loading units on different wagons in Sweden compared with a 25.25 m truck.

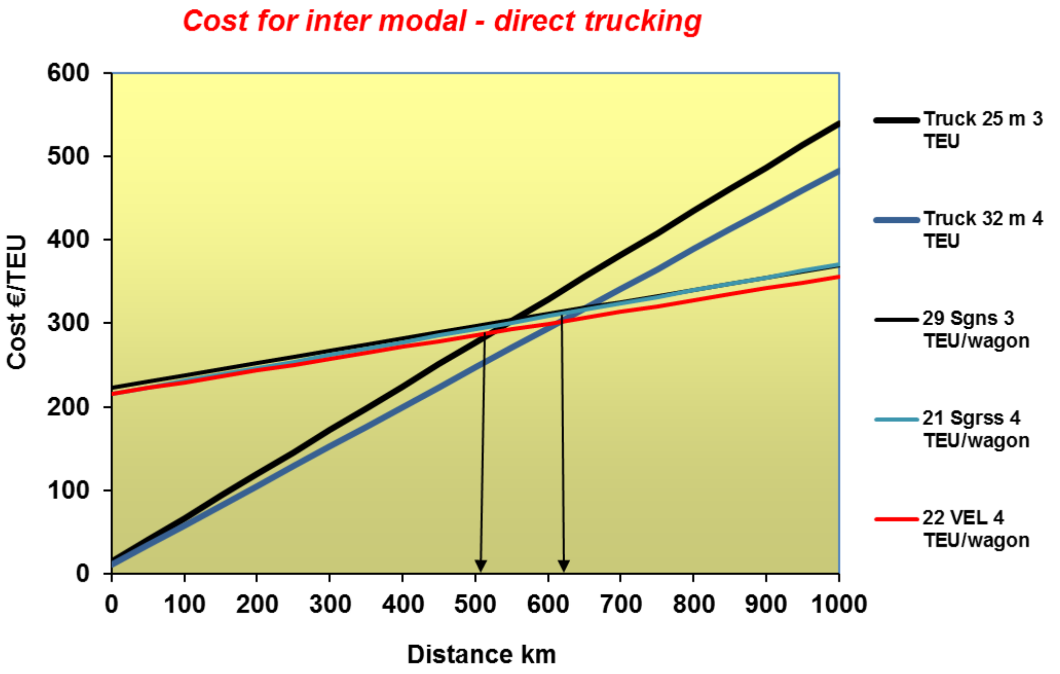


Figure 6.13: Transport cost per ton for an intermodal transport with 20 ft containers on different wagons in Sweden compared with a 25.25 m truck and a 32 m experiment truck .

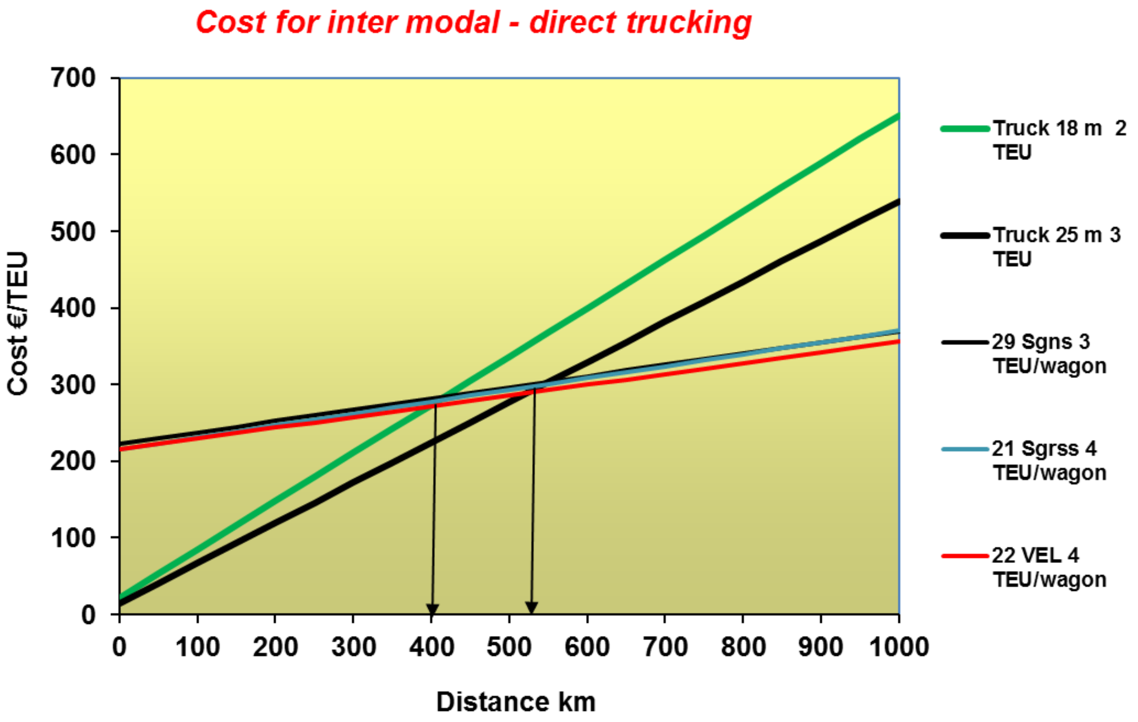


Figure 6.14: Transport cost per ton for an intermodal transport with 20 ft containers on different wagons in Sweden compared with a 25.25 m truck and a 18 m EU truck.

7 Effects of longer and heavier trains

7.1 Prerequisites for longer trains

The train lengths in Europe vary in different countries and lines. In a long term perspective train lengths has successively been increased. In figure 7.2 there is an overview of normal maximum train lengths in Europe. As can be seen there are three main groups:

- 740-750 m in most countries in central Europe as Germany, France, Poland and GB
- 600-730 m in Scandinavia, Italy and Slovakia
- < 600 m in Spain and Portugal

Then there are exceptions, some lines in Denmark and France allows 835-850 m long trains. 1050 m long trains has been tested in Netherlands and Germany at the Betuwe line. In the Marathon project trains of 2x750 = 1,500 m has been operated as an experiment in France. In US train lengths of 2,000-3,000 m are common but the operational prerequisites are different compared with Europe.

Train lengths of 740 – 1,050 m has been recommended in Europe in TSI and for building of new lines and on the TEN-T network 740 m train lengths has been stipulated to be introduced until 2030 of EU for the TEN-T-network, se figure 7.3. 740-750 m are the standard which have been applied in many countries for building and upgrading railways in Europe and are also implemented in many countries as the maximum train length. However, this does not mean that it is possible to operate 740 m on all main lines, there are still much to do to get this standard in the many important RFC in Europe.

At the same time 1,050 m train length has been planned for some lines. This is an optimal train length because a modern 4-axle electric loco can haul 2,200-2,600 gross tonnes and an intermodal train weights approximately 2 tons/meter. That means that 1,000 m wagon rake weight 1,000x2= 2,000 tons with a marginal for variations and heavier freight. That´s why a total train length of 1,050 m are a good alternative for freight lines or corridors which can be introduced on long term.

The capacity increase of longer trains is evident and proportional with the train lengths. In table 7.4 above the increase of the wagon rake length of a train with one locomotive is calculated for different maximum train lengths. In comparison with the lowest length, 550 m, the capacity will increased with 94 % be almost doubled when the train length will extend to the longest length, 1,050 m. A step from 630 m which is normal in Scandinavia, to 740 m train length will increase the train capacity with 18 % and to 835 m by 34 %. An increase form 740 m, the stipulated standard for TEN-T network at 2030, to 1,050 m the maximum train length in TSI will increase the capacity with 43 %.

However, there will also be a loss of capacity because a longer train occupy the signalling blocks longer time than a shorter train. This reduces the line capacity compared with the train capacity, which is illustrated for a double track in figure 7.5.

Furthermore, railway undertakings (RU) revenues could substantially increase while cost would rise only marginally. The graphs in figure 7.1 below clearly indicate that there is a demand for increased length as well as for increased weight. Between 2010 and 2013 the train length was increased from 650 meter to 835 meter, the train weight was increased from 1,600 metric tons up to 2,300 metric tons between Germany and Denmark in the relation Maschen - Fredericia vv.

The increase of utilization of about 19 % led to a decrease of costs per unit by about 14 %. The strengthened competitiveness led to an increase of market share by more than 25 % between 2010 and 2013. At the end the RU run not only better utilized trains but also more trains (+ 7%).

It is also interesting to notice that both graphs still indicate the same pattern even after the implementation of prolonging the train length and the increment of the train weight. The conclusion must be that cargo volumes available for rail freight still are higher than the supply of freight capacity

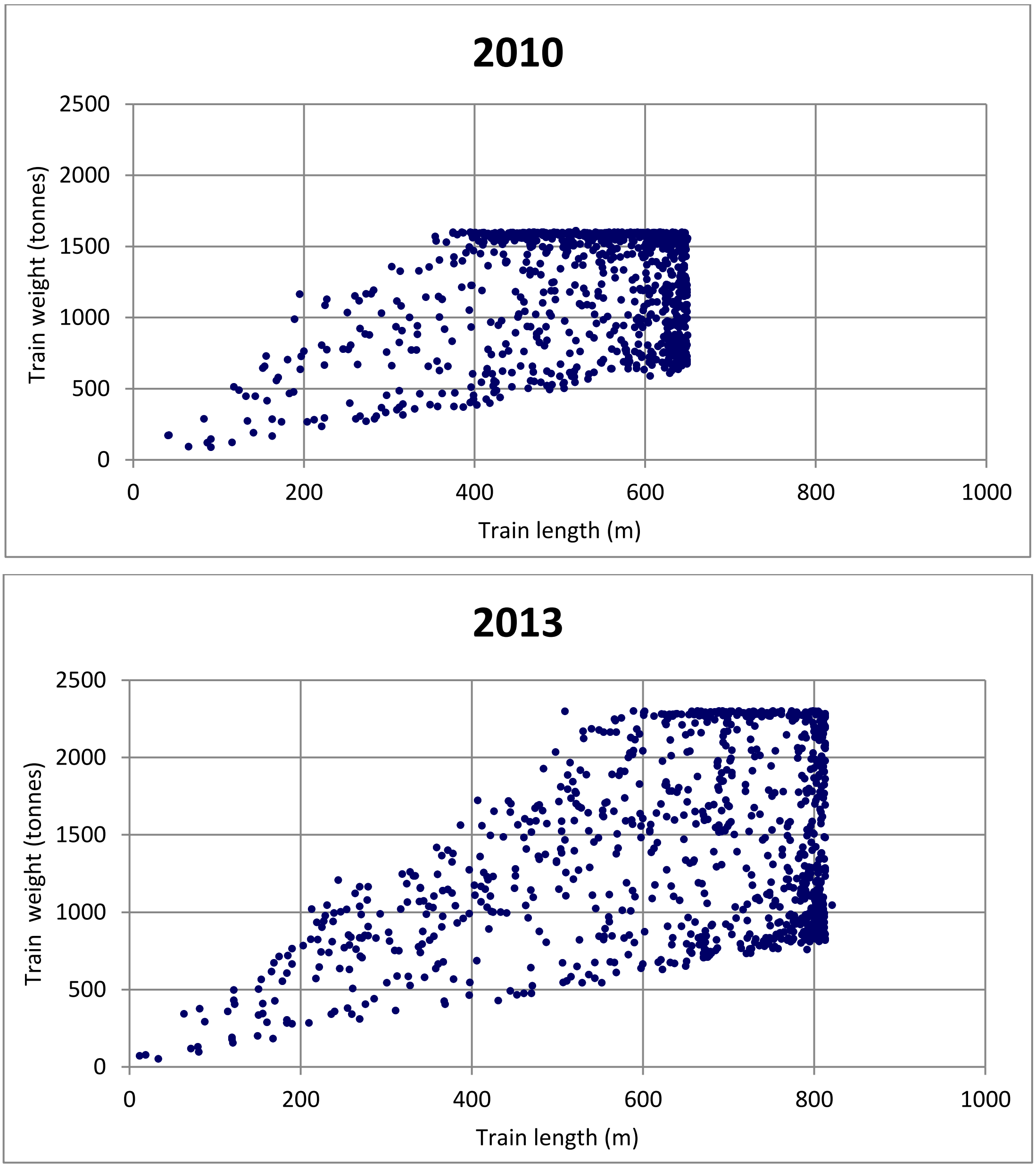
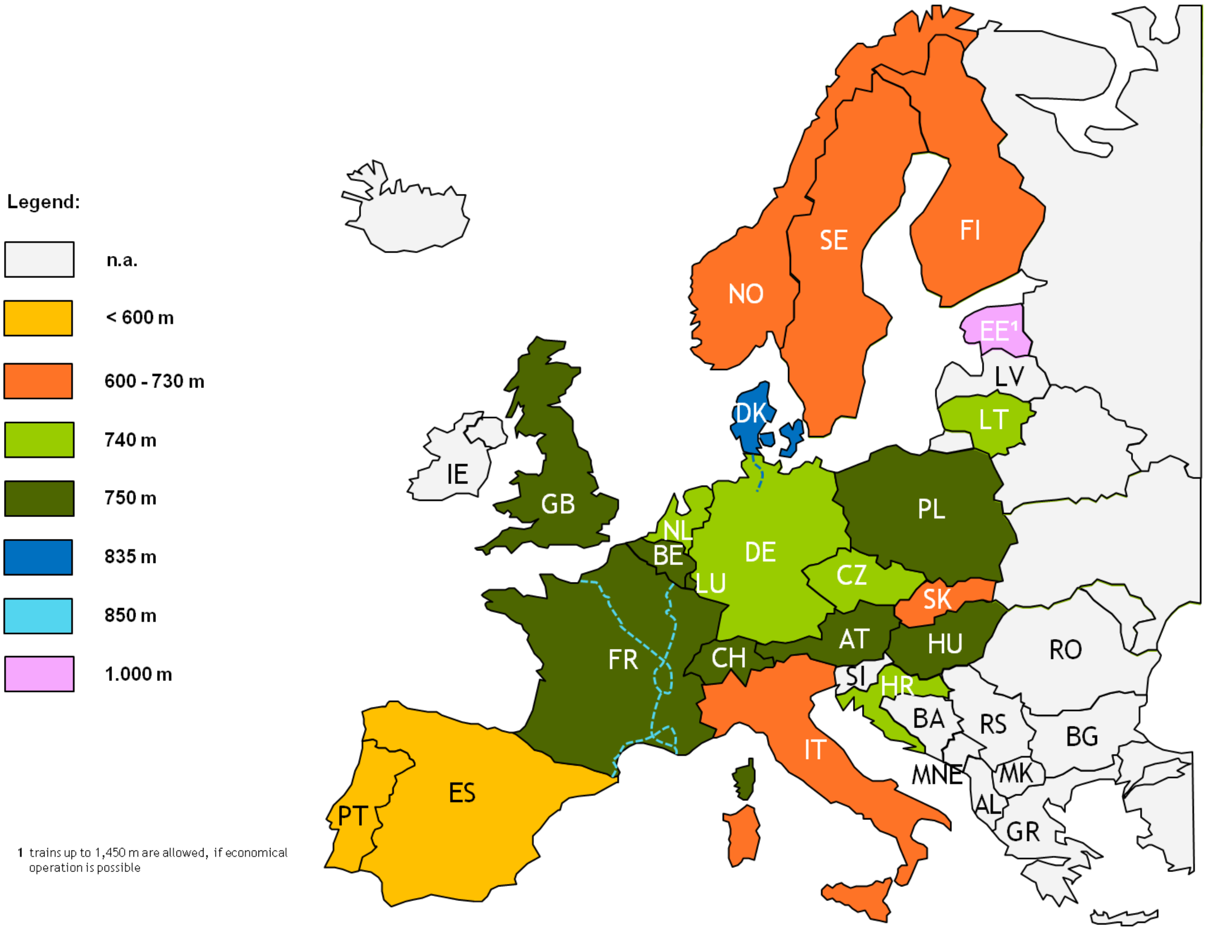


Table 7.1: Trains utilization effects 2010-2013 between Maschen in Germany and Fredericia in Hamburg when train length was extended from 650 to 835 m and train weight from 1,600 t0 2,300 tonnes. Source: Longer Trains Utilization Effects, DB Schenker, 2014.



1 trains up to 1,450 m are allowed, if economical operation is possible

Figure 7.2: Overview of standard maximum trains length per country (Source: CER). There are exceptions from this map i.e. 750 m train lengths on some lines in Germany.

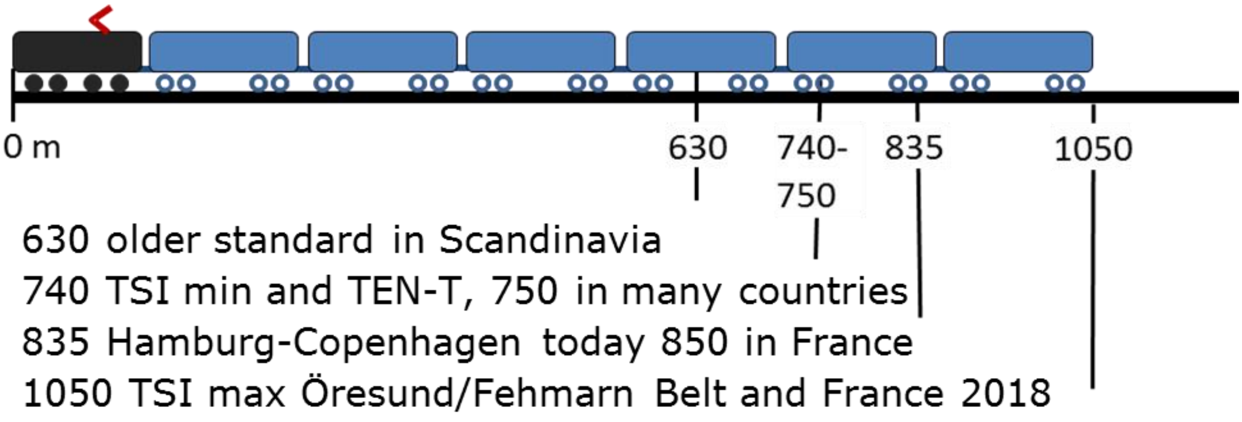


Figure 7.3: Common train lengths today in Europe and possible train lengths in the future. Source: KTH.

Table 7.4: Increase in train capacity with longer trains according to different train lengths.

length (m)	Loco-motive 18,9	Wagon-rake length	Capacity increase vs 550 m	Capacity increase vs 630 m	Capacity increase vs 740 m	Capacity increase vs 835 m
550	18,9	531	0%	-13%	-26%	-35%
630	18,9	611	15%	0%	-15%	-25%
740	18,9	721	36%	18%	0%	-12%
835	18,9	816	54%	34%	13%	0%
1050	18,9	1031	94%	69%	43%	26%

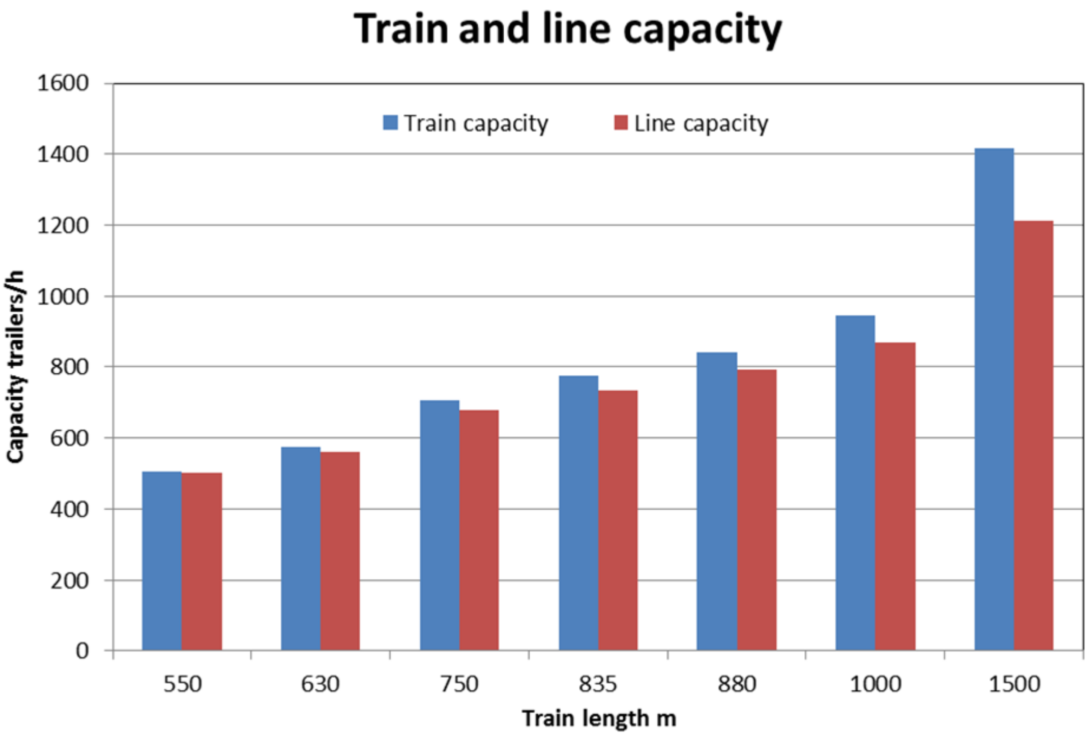


Table 7.5: Increase in train capacity with longer trains and the effect of the line capacity.

7.2 Introduction to cost and capacity calculations

In this chapter costs for operating different train products depending on train lengths is described: Wagon Load (WL), Train Load (TL), Inter Modal Container train (IM container) and Inter modal Trailer Train (IM trailer).The train lengths are the most common in Europe completed with possible future train lengths: 630, 740, 835 and 1,050 m including locomotives.

The costs and capacity has been calculated by KTH cost model (see chapter 6.1). In general there is one cost for the locomotive depending on number of locomotive and locomotive type (size) and one cost per wagon depending on wagon type and load. The calculations had been made for different relations but all with an average length around 1,000 kilometres. All calculations have been made for long haul trains with electric locomotives and not include terminal or marshalling costs or feeder transports.

The costs have been calculated both with track fees and without track-fees as requested in SP5 for the socio-economic calculations, but here costs with track fees is presented. The track access charges for WL, IM container and IM trailer is an average of Swedish, Danish and German track-fees, with a fee of 2,70 €/train (locomotive) kilometres and 0.0007 € per gross tonnes kilometres. This has been chosen to get a representative value which both is depending of the train kilometres and by that reflecting the capacity cost for the infrastructure and the gross tonnes kilometres and by that the maintenance cost for the track. The track access cost for the TL, which is a Swedish example are 0.55 € kilometres and 0.0004 € per gross tonnes kilometres.

7.3 Wagon load

For wagon load, calculations of costs and capacity are showed by table 7.6 and figure 7.7. The calculation is made for a wagon load train with Habbins-wagons i.e. with paper products from Hallsberg to Maschen, distance 1,007 km.

The 630 m train has one standard 4-axle electric locomotive like the TRAXX- locomotive with 5.6 MW and 21 tonnes axle load, 26 wagons with 22.5 tonnes axle load and a gross weight of 1,927 tonnes. The 740 m train has 30 wagons and one 4-axle locomotive and a gross weight of 2,224 tonnes. The capacity will increase with 15 % and the cost per net tonnes-kilometre will decrease with 8% compared with the 630 m train.

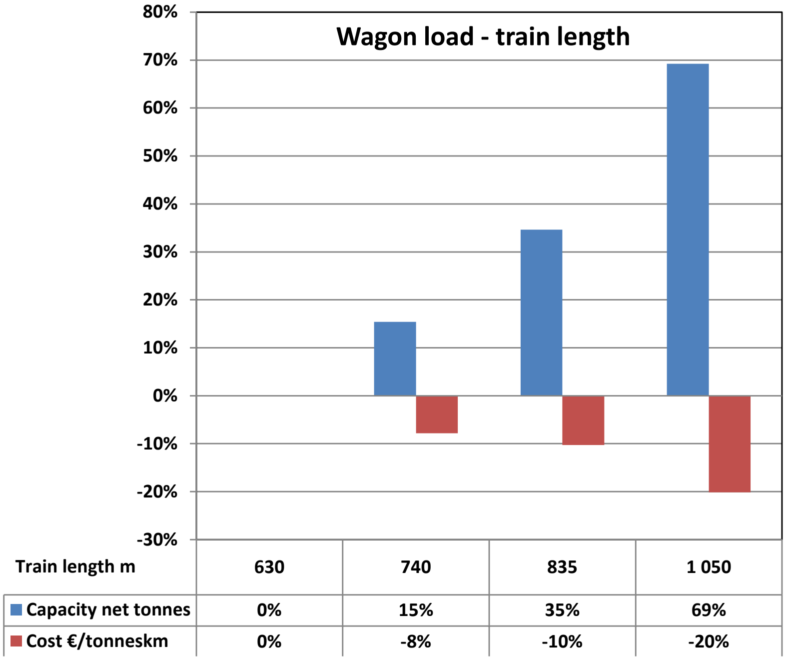
Extended to 835 m there will be 35 wagons and the gross weight will increase to 2,594 tonnes so there is a need for a 6-axle locomotive, like the Danish EG-locomotive which has 6.5 MW and more adhesive weight. The cost for the locomotive will increase with 11 % per kilometre but the cost per net tonnes will decrease with 10 % and the capacity will increase with 35 %.

A train with 1,050 m length can include 44 wagons and will get a gross weight of 3,262 tonnes. With a 6-axle locomotive the cost per net-tonne will decrease with 20 % and the capacity will increase with 69 % compared with the 630 m train.

One important factor is that if the operator can handle more wagons per train it will not only reduce the cost per wagon, it will also increase the possible incomes and the profitability.

Table 7.6: Transport cost per ton for Wagon Load trains with different length and weight. Source: KTH cost calculations.

Product	Wagon load paper rolls		1007 km	Hallsberg-Maschen
Locomotive	4-axle electric 21,0	4-axle electric 21,0	6-axle electric 22,0	6-axle electric 22,0
Wagon type	Habbins 22,5	Habbins 22,5	Habbins 22,5	Habbins 22,5
Gross ton	1 927	2 224	2 594	3 262
Max. train length (m)	630	740	835	1 050
Actual length (m)	625	718	835	1 045
No of locos	1,0	1,0	1,0	1,0
No of wagons	26	30	35	44
Operating costs				
€/loco km	8,43	8,43	9,35	9,35
€/wagon km	0,27	0,27	0,27	0,27
€/train km	15,44	16,52	18,80	21,23
Capacity				
Net tonnes/train	1 040	1 200	1 400	1 760
Index	100	115	135	169
Change	0%	15%	35%	69%
Cost/Capacity				
Cost/nettonkm	0,0148	0,0138	0,0134	0,0121
Cost/nettonkm*	0,0174	0,0161	0,0157	0,0139
*)Incl empty runs				
Index incl empty runs	100	92	90	80
Change	0%	-8%	-10%	-20%



Train length m	630	740	835	1 050
🟦 Capacity net tonnes	0%	15%	35%	69%
🟥 Cost €/tonneskm	0%	-8%	-10%	-20%

Figure 7.7: Transport cost per tonnes-kilometres and capacity in gross tonnes for Wagon Load trains with different length and weight. Source: KTH cost calculations.

7.4 Train load with different locomotives

For train load with high density goods, the train length is mostly not a restriction because they are often much shorter than the maximum train length. Instead, train weight and axle load are important factors. The axle load are analysed in next chapter about the wagons. Here different train weights hauled by different locomotives will be presented.

The train weight a locomotive can haul are dependent of the locomotive itself, the wagons and the infrastructure. Most important for the locomotives are the maximum (continuous) traction power and maximum traction force as well as adhesion weight. The available wheel-rail adhesion is also critical to performance and not only depends on how “slippery” the track is but also on the locomotive’s slip control.

The performance of the infrastructure is important especially track gradients (uphill/downhill) and the curves. The performance of wagons in terms of aerodynamic resistance and rolling resistance can also affect the maximum train weight, but this is the least important factor.

As regards the freight transportation system, development has technically speaking always been incremental. Performance has gradually improved from the first steam locomotives, but it is the tractive power – the locomotives – that has often determined the standard of the trains and the infrastructure. So far we have had a new standard roughly every 50 years as follows which is an example from Sweden, see also figure 7.8:

- The electric D-loco was introduced in 1925 and electrification began. Freight trains weighed 900 tons and were 500 metres long, the axle load was 18 tons, speed 70 km/h, the rail weight 43 kg/m and the signalling system was manual operated. This standard lasted until
- The Rc-loco appeared in 1967. Freight trains weighed 1,500 tons and were 630 metres long, the axle load was 20 tons, speed 90 km/h, the rail weight 50 kg/m and the signalling system was automatic block system on double track. This standard lasted until the
- The TRAXX locos arrived in Sweden in 2010. Freight trains can weigh 2,000 tons and be 630 metres long, the axle load is 22.5 tons, the rail weight is 60 kg/m and the signalling system is Centralised traffic control (CTC) with ATC.

What standard we want to have in 2030-2050 is something that we have to decide now. It takes 40-50 years to establish a new standard so we need to ask ourselves if the performance we have today is the optimal performance for the future. Is the next step longer, heavier trains and even higher axle loads? We can see from the figure 7.9 what gains can be made in capacity and cost by improving the train system’s performance.

1925: D loco

- Train weight 900 tons
- Train length 500 m
- Axle load 18 tons
- Max speed 70 km/h
- Rail weight 43 kg/m
- Manual signalling system

1967: Rc loco

- Train weight 1,500 tons
- Train length 630 m
- Axle load 20 tons
- Max speed 90 km/h
- Rail weight 50 kg/m
- Automatic block signalling

2010: TRAXX loco

- Train weight 2,000 tons
- Train length 630 m
- Axle load 22.5 tons
- Max speed 100 km/h
- Rail weight 60 kg/m
- ATC/CTC signalling

Figure 7.8: Tractive power, freight trains and infrastructure in a historical perspective, example from Sweden.

2010: TRAXX loco

- Train weight 2,000 tons
- Train length 630 m
- Axle load 22.5 tons
- Max speed 100 km/h
- Rail weight 60 kg/m
- ATC/CTC signalling system

2030: XX loco

- Train weight 5,000 ton
- Train length 1,050 m
- Axle load 25.0 tons
- Max speed 120 km/h
- Rail weight 60 kg/m
- ERTMS L-2 signalling

2050: XXX loco

- Train weight 10,000 ton
- Train length 2,100 m
- Axle load 30.0 tons
- Max speed 140 km/h
- Rail weight 71 kg/m
- ERTMS L-3 signalling

Figure 7.9: Tractive power, freight trains and infrastructure in a future perspective.

The locomotives used in the calculations of train load are presented in table 6.19. The results of the calculations are showed by table 7.10 and figure 7.11. The calculations are made for a Swedish steel train with coils with Shimms-wagons from Luleå to Borlänge, distance 999 km. In this case, the train length is less than 500 m and is not a restriction because the linear load per metre is so high. So the performance of the locomotive, the number of locomotives and the axle load are the most important factors.

This train has today a maximum gross weight of 3,200 tonnes in 32 wagons and need two standard 4-axle locomotives with 21 tonnes axle load and 5.6 MW (as the TRAXX loco) because of the steep grades of 17 ‰ in northern Sweden. Today the wagons are permitted to load 25 tonnes axle load in the loading direction but the locomotives have 21.0 tonnes axle load. A normal train have 32 wagons, is 423 m long and have a payload of 2,528 net tonnes.

If we increase the axle load on the locomotive to 22.0 tonnes (as the Vectron loco) we assume that we can handle 3,600 gross tonnes in 36 wagons with two locomotives. By that the payload increase by 13 % to 2,844 net tonnes and the cost decrease with 5 % per net tonne-km including empty runs. The investment and running costs for the locomotive has assumed to be same as for a loco with 21.0 tonnes axle load.

By using two 6-axle locomotives with 22.0 tonnes axle load (as the Transmontana loco) we can increase the train weight to 5,600 tonnes in 56 wagons. The capacity will increase by 75 % to 4,424 net tonnes and the cost will decrease by 16 % per net tonne km.

Next step is to increase the axle load on the locomotive to 25.0 tonnes just as the wagons which is technically possible today. For this future locomotive we had assumed the same cost as a 6-axle loco today. With two locos and a assumed train weight of 6,000 tonnes we can handle 4,740 net tonnes in 60 wagons. The capacity will increase with 88 % and the cost will decrease by 18 % per net tonne km. Theoretically it may be possible to handle 64 wagons 6,400 gross tonnes but then the train will be longer than 750 m which is the planned future maximum train lengths on the actual lines.

With only one 6-axle locomotive with 25.0 tonnes axle load it is probably possible to handle the same gross weight as with two 4-axle locos with 21.0 tonnes axle load today, 3.200 gross tonnes. By that it is possible to reduce the cost by 13 % per tonne km but the capacity is still the same as today.

Table 7.10: Locomotives with assumed performance and costs used in the calculations for steel train load in Sweden. Source: KTH cost calculations.

Traction		Electric	Electric	Electric	Electric/duc	Electric/duo
Axles	No	4-axle	4-axle	6-axle	4-axle	6-axle
Axle load	tonnes	21,0	22,0	22,0	22,5	25,0
Year		2010	2015	2017	2020	2030
Type (example)		TRAXX	Vectron	Transmontana		
Tractive effort KW	kW	5 600	6 400	8 400	7 000	10 000
Max speed	km/h	140	200	140	160	120
Axles/locomotive	number	4	4	6	4	6
Adhesive weight	tonnes	84	88	132	90	150
Gross wight	tonnes	84	88	132	90	150
Length	meter	18,9	19,0	19,8	19,0	21,0
Energy consumption	KWh/locokm	5,00	5,00	6,00	5,00	7,00
Energy consumption	l/locokm	0,00	0,00	0,00	0,00	0,00
Maintenance cost	SEK/locokm	6,00	6,00	8,00	6,00	8,00
Investment cost	SEK	35 000	35 000	45 000	35 000	45 000
Life time	years	25	25	25	25	25
Max train weight in Sweden						
On 10 ‰ lines	tonnes	2 200	2 400	3 600	2 600	4 400
On 17 ‰ lines	tonnes	1 600	1 800	2 800	1 900	3 200
Number of locos		2	2	2	2	2
On 17 ‰ lines	tonnes	3 200	3 600	5 600	3 800	6 400

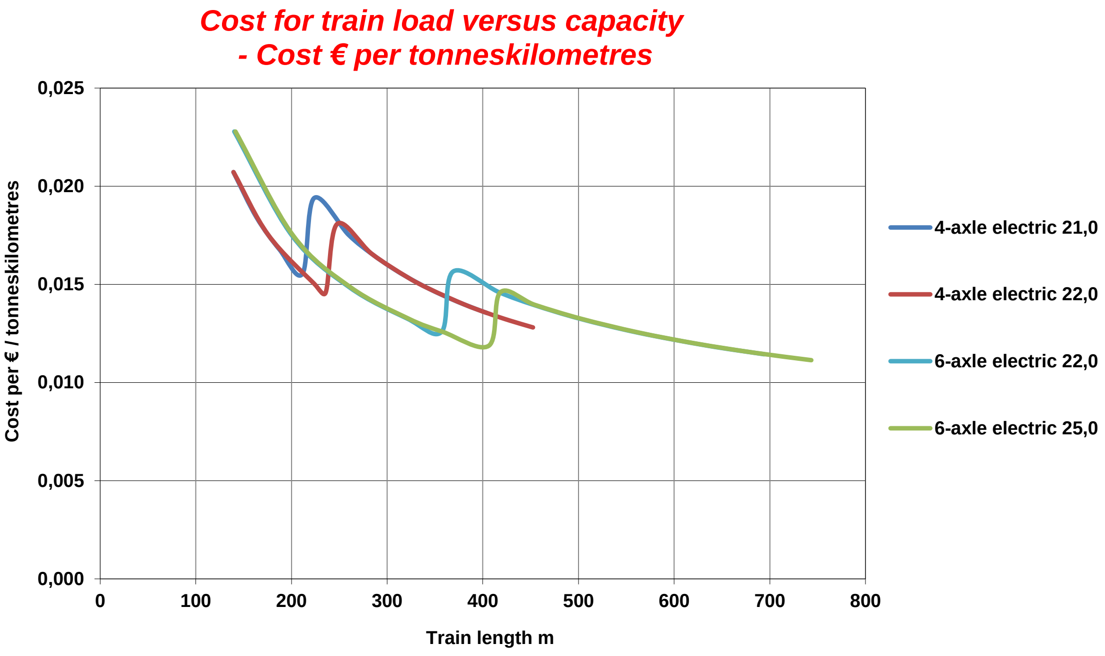


Figure 7.11: Train length and transportation costs for steel train load in Sweden with locomotives with assumed performance as in table above. The knees in the diagram are the shift from one to two locomotives. Source: KTH cost calculations.

Table 7.12: Transport cost per ton for Train Load trains with different locomotives. Source: KTH cost calculations.

Product	Train load steel coils		999 km	Luleå-Borlänge	
Locomotive - axle load	4-axle electric 21,0	4-axle electric 22,0	6-axle electric 22,0	6-axle electric 25,0	6-axle electric 25,0
Wagon type - axle load	Shimmns 25	Shimmns 25	Shimmns 25	Shimmns 25	Shimmns 25
Gross tonnes	3 200	3 600	5 600	6 000	3 200
Max. train length (m)	750	750	750	750	750
Actual length (m)	423	471	714	743	427
No of locos	2	2	2	2	1
No of wagons	32	36	56	60	32
Operating costs					
€/loco km	7,94	7,94	9,48	9,48	5,81
€/wagon km	0,37	0,37	0,37	0,37	0,37
€/train km	19,81	21,29	30,26	31,74	17,68
Capacity					
Net tonnes	2 528	2 844	4 424	4 740	2 528
Index	100	113	175	188	100
Change	0%	13%	75%	88%	0%
Cost/Capacity					
Cost/nettonkm	0,0078	0,0075	0,0068	0,0067	0,0070
Cost/nettonkm*	0,0128	0,0121	0,0108	0,0106	0,0111
*)Incl empty runs					
Index	100	95	84	82	87
Cost	0%	-5%	-16%	-18%	-13%

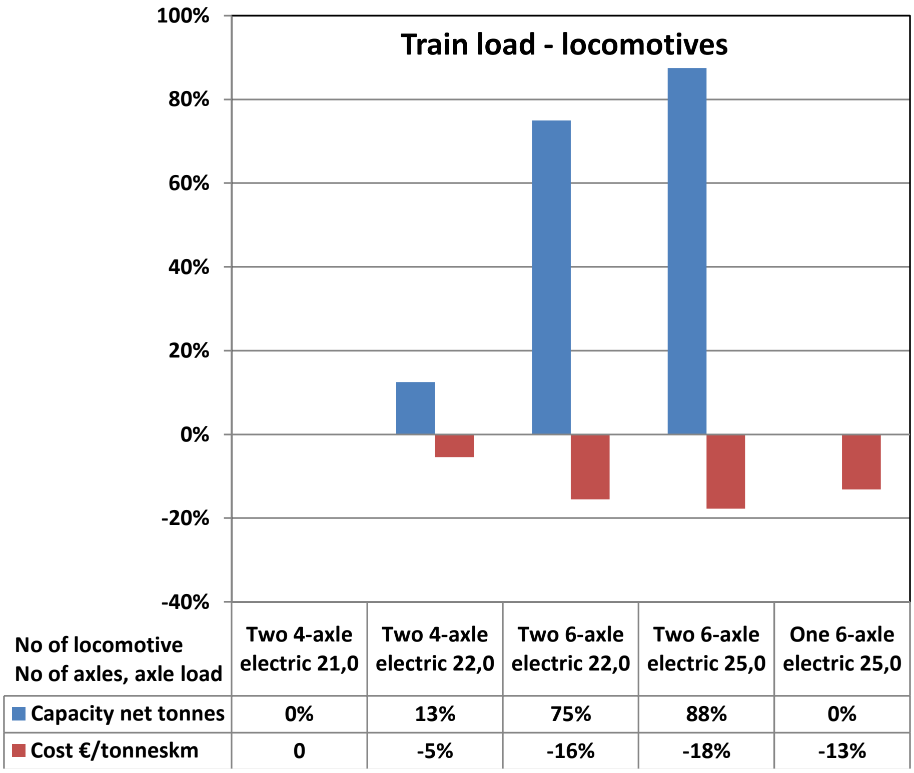


Figure 7.13: Transport cost per tonnes-kilometres and capacity in gross tonnes for Train Load trains with different locomotives. Source: KTH cost calculations.

7.5 Inter Modal container trains

For inter modal container trains, calculations of costs are showed by table 7.14 and figure 7.15. The calculation is made for an inter-modal container train with Sggrss-wagons with Jacob-bogies loading two 40 foot containers from Hallsberg to Maschen, distance 1,007 km.

The 630 m train has one standard 4-axle locomotive with 5.6 MW (like TRAXX), 22 wagons and a gross weight of 1,343 tonnes. The 740 m train has 26 wagons and one 4-axle locomotive and a gross weight of 1,555 tonnes. The capacity will increase with 18 % and the cost per TEU-kilometre will decrease with 9 %.

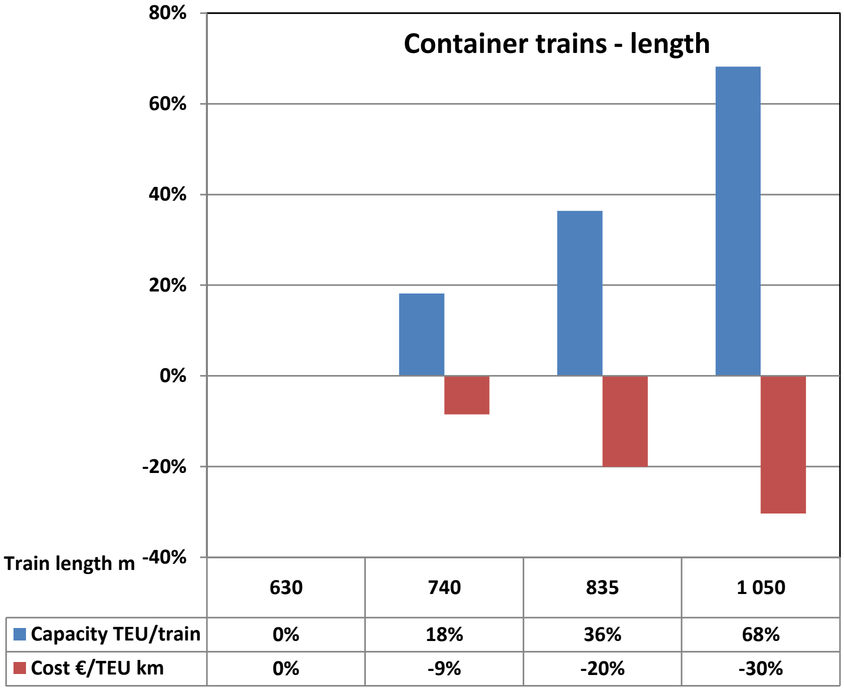
Extended to 835 m there will be 30 wagons and the gross weight will increase to 1,980 tonnes. The cost per TEU will decrease with 20 % and the capacity will increase with 36 %.

A train with 1050 m length can include 37 wagons and will get a gross weight of 2.616 tonnes so there is a need for a 6-axle locomotive, like the Danish EG-locomotive which has 6.5 MW and more adhesive weight. The cost for the locomotive will increase by approximately 10 % per km but the cost per net-tonne kilometre will decrease with 30 % because of the capacity which will increase with 68 % compared with the 630 m train.

One important factor is that if the operator can handle more wagons per train it will not only reduce the cost per wagon, it will also increase the possible incomes and by that the profitability.

Table 7.14: Transport costs for Inter Modal container trains with different length and weight. Source: KTH cost calculations.

Product	Inter Modal	Container	1007 km	Hallsberg-Maschen
Locomotive	4-axle electric 21,0	4-axle electric 21,0	4-axle electric 21,0	6-axle electric 22,0
Wagon	6axl 80ft Sggrss	6axl 80ft Sggrss	6axl 80ft Sggrss	6axl 80ft Sggrss
Gross ton	1 343	1 555	1 980	2 616
Max. train length (m)	630	740	835	1 050
Actual length (m)	617	726	835	1 025
No of locos	1	1	1	1
No of wagons	22	26	30	37
Operating costs				
€/loco km	7,92	7,92	7,92	8,69
€/wagon km	0,23	0,23	0,23	0,23
€/train km	12,97	13,89	14,80	17,18
Capacity				
No of TEUs/wagon	4	4	4	4
No of TEUs/train	88	104	120	148
Change	0%	18%	36%	68%
Cost/Capacity				
Cost €/TEU km	0,17	0,15	0,13	0,12
Index cost/TEU km	100	91	80	70
Change	0%	-9%	-20%	-30%



Train length m	630	740	835	1 050
🟦 Capacity TEU/train	0%	18%	36%	68%
🟥 Cost €/TEU km	0%	-9%	-20%	-30%

Figure 7.15: Transport cost per tonnes-kilometres and capacity in gross tonnes for Inter Modal container trains with different length and weight. Source: KTH cost calculations.

7.6 Inter Modal trailer trains

For inter modal trailer trains, calculations of costs are showed by table 7.16 and figure 7.17. The calculation is made for an inter-modal trailer train with Sdggmrss-wagons with Jacob-bogies loading two 13.75 m trailers from Helsingborg to Duisburg, distance 984 km.

The 630 m train has one standard 4-axle locomotive with 5.6 MW (like TRAXX), 17 wagons and a gross weight of 1,649 tonnes. The 740 m train has 21 wagons and one 4-axle locomotive and a gross weight of 2,037 tonnes. The capacity will increase with 24 % and the cost per net tonnes-kilometre will decrease with 11 %.

Extended to 835 m there will be 23 wagons and the gross weight will increase to 2,231 tonnes. The cost per net-tonnes will decrease with 15 % and the capacity will increase with 35 %.

A train with 1,050 m length can include 30 wagons and will get a gross weight of 2,910 tonnes so there is a need for a 6-axle locomotive, like the Danish EG-locomotive which has 6.5 MW and more adhesive weight. The cost for the locomotive will increase by approximately 10 % per km but the cost per net-tonne kilometres will decrease with 21 % because of the capacity which will increase with 76 % compared with the 630 m train.

One important factor is that if the operator can handle more wagons per train it will not only reduce the cost per wagon, it will also increase the possible incomes and by that the profitability.

Table 7.16: Transport costs for Inter Modal trailer trains with different length and weight. Source: KTH cost calculations.

Product	Inter Modal	Trailer	984 km	Helsingborg-Duisbu
Locomotive	4-axle electric 21,0	4-axle electric 21,0	4-axle electric 21,0	6-axle electric 22,0
Wagon	6-axle Sdggmrss	6-axle Sdggmrss	6-axle Sdggmrss	6-axle Sdggmrss
Gross ton	1 649	2 037	2 231	2 910
Max. train length (m)	630	740	835	1 050
Actual length (m)	600	737	806	1 045
No of locos	1	1	1	1
No of wagons	17	21	23	30
Operating costs				
€/loco km	7,66	7,66	7,66	8,43
€/wagon km	0,35	0,35	0,35	0,35
€/train km	13,63	15,04	15,74	18,98
Capacity				
No of trailers/wagon	2	2	2	2
No of trailers/train	34	42	46	60
Change	0%	24%	35%	76%
Cost/Capacity				
Cost €/trailer km	0,40	0,36	0,34	0,32
Index	100	89	85	79
Change	0%	-11%	-15%	-21%

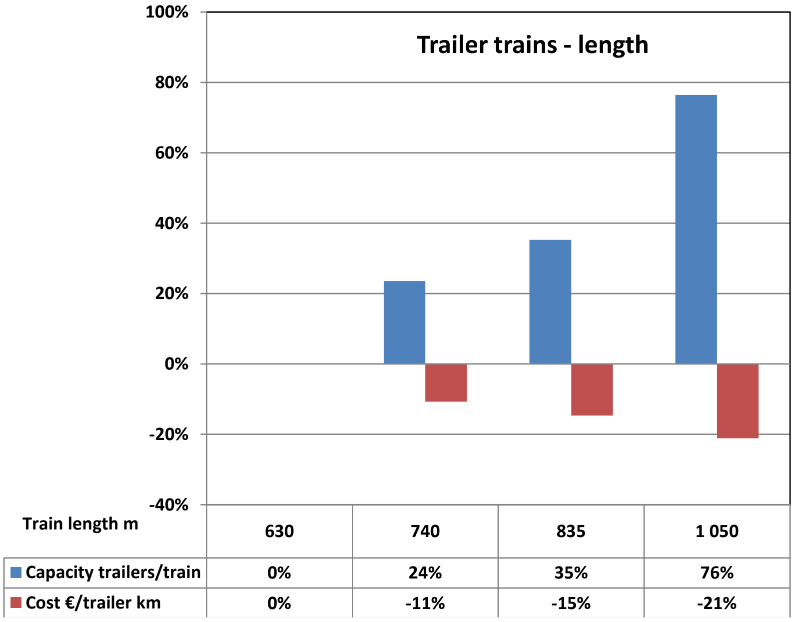


Figure 7.17: Transport cost per tonnes-kilometres and capacity in gross tonnes for Inter Modal trailer trains with different length and weight. Source: KTH cost calculations.

8 Cost and capacity for operating different wagons - MS 23 in WP 2.2

In this chapter costs for operating different wagons in the above mentioned train products: Train Load (TL), Wagon Load (WL), Inter Modal Container train (IM container) and Inter modal Trailer Train (IM trailer) is described. The costs and capacity has been calculated by KTH cost model (see chapter 6.1). The costs have been calculated with track fees. Calculations have been made for the same wagons which have been evaluated in the report MS 15 "Scenarios of development of new rail freight vehicles" in WP 2.2. Therefore the wagons are presented in the same order as in report MS 15. This chapter is also the final report MS 23 "Business cases and validation" which has been integrated in this report.

8.1 Inter modal container wagons for 45 ft containers

The wagon concepts which have been analysed in this section are:

- A 6-axle bogie wagon with 2 frames and Jacob-bogie as a reference
- A 12-axle bogie wagon with 5 frames and Jacob-bogies the new concept
- A 4-single-axle pair-coupled wagon
- Three coupled bogie-wagons for a combination of 40+45+40 foot containers

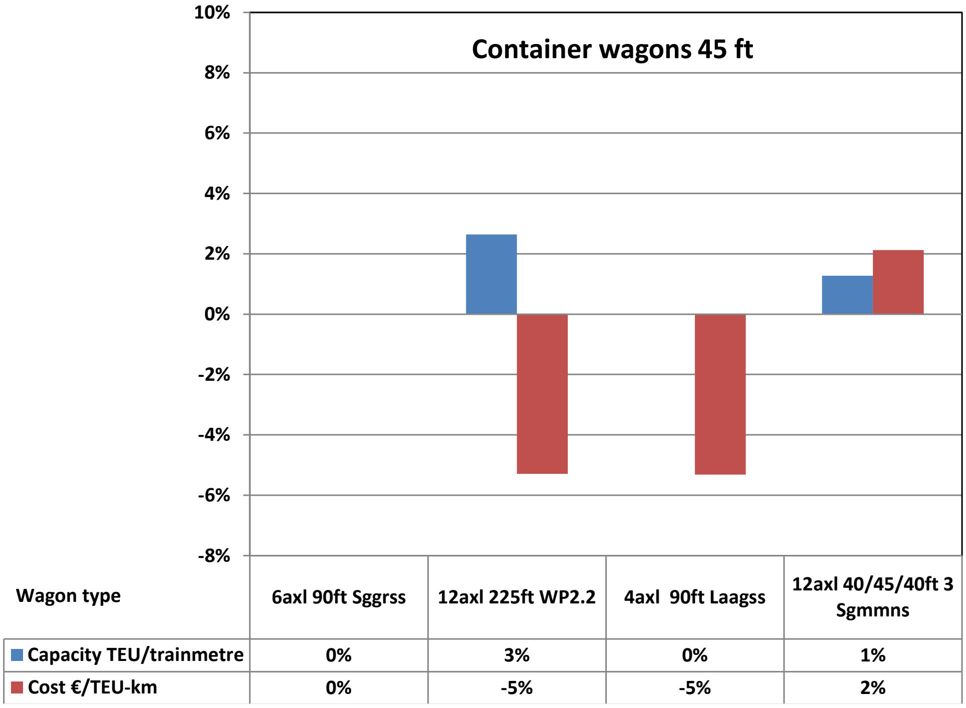
The 12-axle bogie-wagon and the three coupled bogie-wagons are the new concepts defined in WP.2.2. The other wagons are existing conventional wagons.

In table 8.1 detailed data from the calculations are shown and in figure 8.2 the main results of improvement in capacity and costs. The 12-axle 225ft wagon is the most efficient with an increase of 3 % in capacity per train-metre and a decrease of 5 % in cost per TEU-kilometre compared with the reference wagon. The 4 single axle 90ft wagon is also 5 % cheaper but has restrictions in the loading weight for the containers. The 12-axle rebuilt wagon with three bogie-wagons coupled together with foldable support on the middle wagon to carry 40+45+40 foot containers. Because it is rebuilt of older wagon the capital cots has been calculated to only be half of a comparable new wagon. The result is 1% improved capacity but also slightly higher cost with 2 % because of higher operating cost. The advantage is that a very flexible wagon can be built for a low cost of older wagons.

In figure 8.3 the cost for the different wagons depending on train length is shown. The differences between the wagons are not big but the importance filling the trains with wagons and operate long trains is evident.

Table 8.1: Transport costs for Inter Modal container wagons for 45 ft containers. Source: KTH cost calculations.

Product	Inter Modal	Container 45 ft	1007 km	Duisburg-Katrinehol
Locomotive	4-axle electric 21,0	4-axle electric 21,0	4-axle electric 21,0	4-axle electric 21,0
Wagon	6axl 90ft Sggrss	12axl 225ft WP2.2	4axl 90ft Laagss	12axl 40/45/40ft 3 Sg
Gross ton	1 879	1 869	1 766	2 295
Train length (m)	724	734	724	744
No of locos	1	1	1	1
No of wagons	24	10	24	18
Operating costs				
€/loco km	7,27	7,27	7,27	7,27
€/wagon km	0,24	0,55	0,21	0,36
€/train km	12,94	12,76	12,24	13,76
Capacity				
No of TEUs/wagon	4,5	11,25	4,5	6,25
No of TEUs/train	108	112,5	108	112,5
TEU/Trainmetre	0,149	0,153	0,149	0,151
Change	0%	3%	0%	1%
Cost/Capacity				
Cost € per TEUkm	0,120	0,113	0,113	0,122
Index cost/TEU km	100	95	95	102
Change	0%	-5%	-5%	2%



Wagon type	6axl 90ft Sggrss	12axl 225ft WP2.2	4axl 90ft Laagss	12axl 40/45/40ft 3 Sgmmns
🟦 Capacity TEU/trainmetre	0%	3%	0%	1%
🟥 Cost €/TEU-km	0%	-5%	-5%	2%

Figure 8.2: Transport cost per TEU-kilometres and capacity in TEU per train-metre for Inter Modal wagons for 45 ft containers. Source: KTH cost calculations.

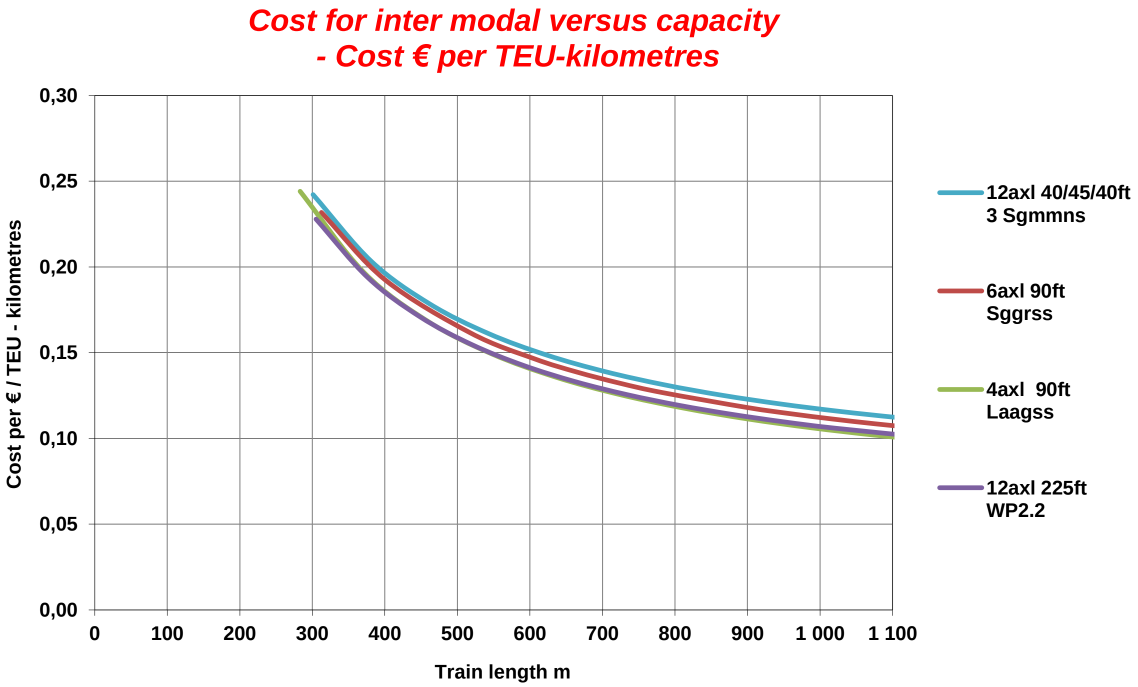


Figure 8.3: Transport cost per TEU-kilometres depending on train length for Inter Modal wagons for 45 ft containers. Source: KTH cost calculations.

8.2 Inter modal container wagons for 40 ft containers

The wagon concepts which have been analysed in this section are:

- A 6-axle bogie wagon with 2 frames and Jacob-bogie as a reference
- A 12-axle bogie wagon with 5 frames and Jacob-bogies, the new concept
- A 4-axle bogie-wagon with one frame, the VEL-wagon

The 12-axle wagon is the new concept defined in WP.2.2. The 6-axle wagon is a conventional wagon as a reference. The 4-axle wagon is developed in another EU-project, the VEL-wagon, and implemented in the market by METRANS.

In table 8.4 detailed data from the calculations are shown and in figure 8.5 the main results of improvement in capacity and costs. The 12-axle 225ft wagon increase the capacity per train-metre with 7 % and decrease the cost with 7 % in cost per TEU-kilometre compared with the reference wagon. The most economical is the 4-axle 80ft bogie wagon (the VEL-wagon) which is 11 % cheaper per TEU-kilometre and has 5% improved capacity compared with the 6-axle 80ft-wagon.

In figure 8.6 the cost for the different wagons depending on train length is shown. The differences between the wagons are bigger than for the 45 ft wagons but still the importance filling the trains with wagons and operate long trains is evident.

Table 8.4: Transport costs for Inter Modal container wagons for 40 ft containers. Source: KTH cost calculations.

Product	Container 40 ft	1007 km	Hallsberg-Maschen
Locomotive	4-axle electric 21,0	4-axle electric 21,0	4-axle electric 21,0
Wagon	6axl 80ft Sggrss	12axl 200ft WP2.2	4axl 80ft Sggnss VEL
Gross ton	1 838	1 848	1 747
Train length (m)	726	720	719
No of locos	1	1	1
No of wagons	26	11	27
Operating costs			
€/loco km	7,92	7,92	7,92
€/wagon km	0,23	0,53	0,18
€/train km	13,89	13,72	12,87
Capacity			
No of TEUs/wagon	4	10	4
No of TEUs/train	104	110	108
TEU/Trainmetre	0,143	0,153	0,150
Change	0%	7%	5%
Cost/Capacity			
Cost € per TEUkm	0,134	0,125	0,119
Index cost/TEU km	100	93	89
Change	0%	-7%	-11%

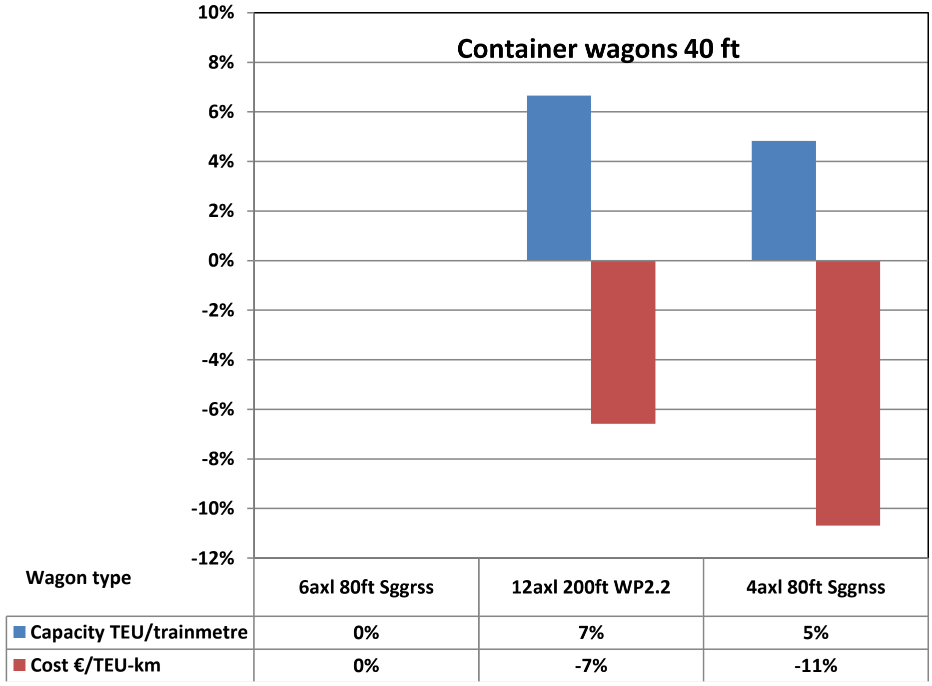


Figure 8.5: Transport cost per TEU-kilometres and capacity in TEU per train-metre for Inter Modal wagons for 40 ft containers. Source: KTH cost calculations.

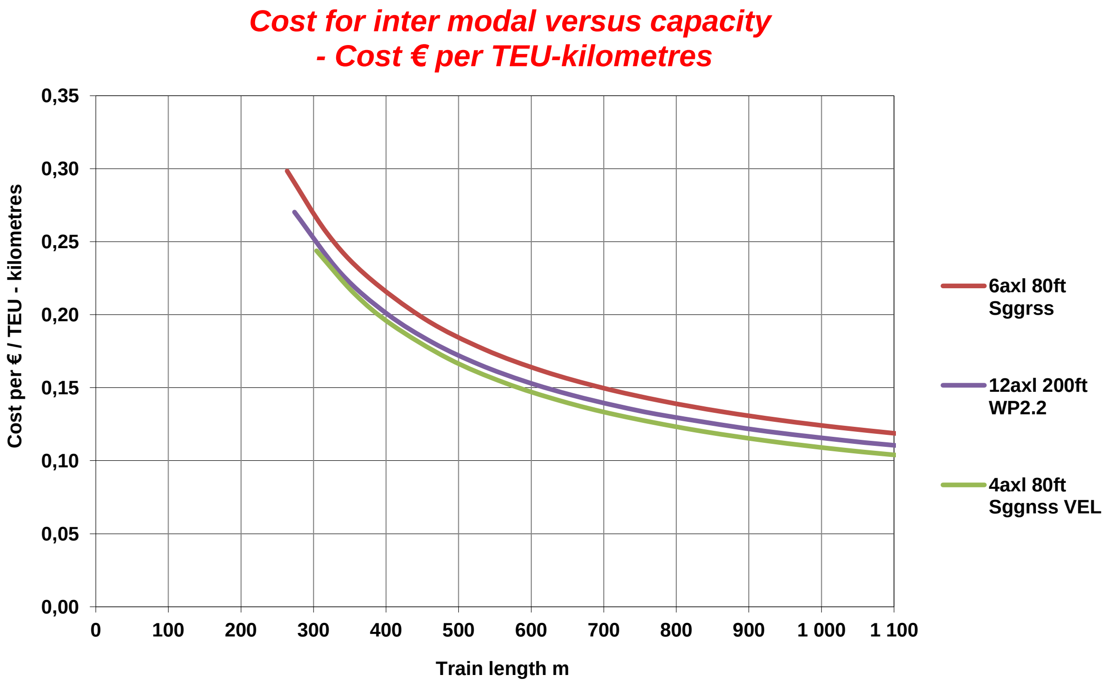


Figure 8.6: Transport cost per TEU-kilometres depending on train length for Inter Modal wagons for 40 ft containers. Source: KTH cost calculations.

8.3 Inter modal trailer wagons for liftable trailers

The wagon concepts which have been analysed in this section are:

- A 4-axle bogie-wagon with one pocket frame as a reference
- A 6-axle wagon with 2 pocket frames and Jacob-bogie
- A 12-axle wagon with 4 pocket frames and Jacob-bogies and draw-bar

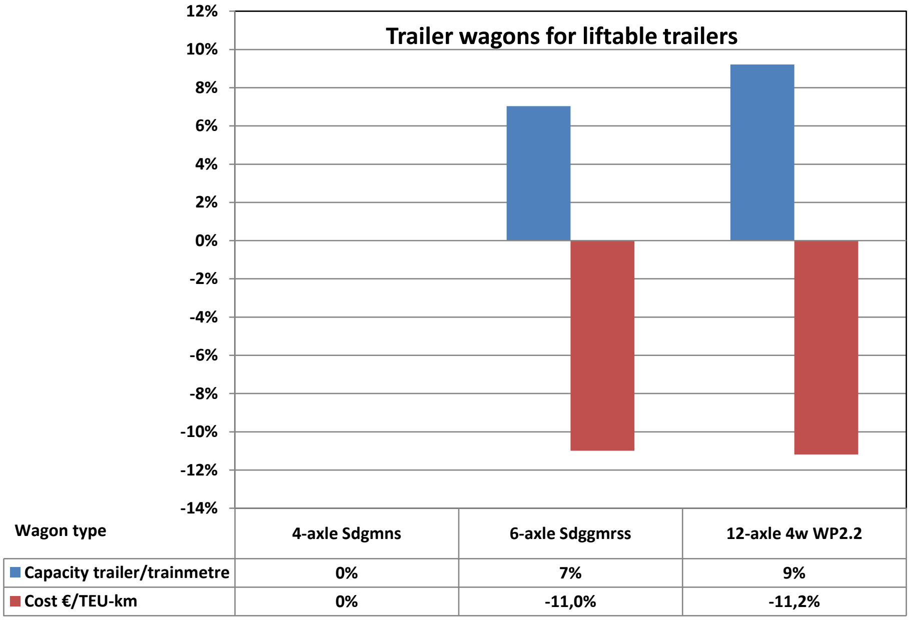
The 12-axle wagon is the new concept defined in WP.2.2. The 6-axle wagon is the most common conventional wagon. The 4-axle wagon is an older pocket wagon still rather common and used as a reference.

In table 8.7 detailed data from the calculations are shown and in figure 8.8 the main results of improvement in capacity and costs. The 12-axle wagon is the most efficient and increase the capacity per train-metre with 9 % and decrease the cost with 11 % in cost per trailer-kilometre compared with the reference wagon. The 6-axle wagon is also 11 % cheaper per trailer-kilometre and has 7 % improved capacity compared with the 4-axle wagon.

In figure 8.9 the cost for the different wagons depending on train length is shown. The differences between the wagons are rather big especially compared with the 4-axle wagon. The importance filling the trains with wagons and operate long trains is still evident.

Table 8.7: Transport costs for Inter Modal wagons for liftable trailers. Source: KTH cost calculations.

Inter Modal	Liftable trailers	984 km	Helsingborg-Duisbu
Locomotive	4-axle electric 21,0	4-axle electric 21,0	4-axle electric 21,0
Wagon	4-axle Sdgmns	6-axle Sdggmrss	12-axle 4w WP2.2
Gross ton	2 009	2 037	2 034
Length m	733	737	722
No of locos	1	1	1
No of wagons	39	21	10,5
Operating costs			
€/loco km	7,66	7,66	7,66
€/wagon km	0,19	0,32	0,65
€/train km	15,09	14,46	14,43
Capacity			
No of trailers/wa	1	2	4
No of trailers/trai	39	42	42
Trailers/Trainmet	0,053	0,057	0,058
Change	0%	7%	9%
Cost/Capacity			
Cost € per trailer	0,39	0,34	0,34
Index	100	114	126
Change	0%	-11%	-11%



Wagon type	4-axle Sdgmns	6-axle Sdggmrss	12-axle 4w WP2.2
🟦 Capacity trailer/trainmetre	0%	7%	9%
🟥 Cost €/TEU-km	0%	-11,0%	-11,2%

Figure 8.8: Transport cost per TEU-kilometres and capacity in TEU per train-metre for Inter Modal wagons for liftable trailers. Source: KTH cost calculations.

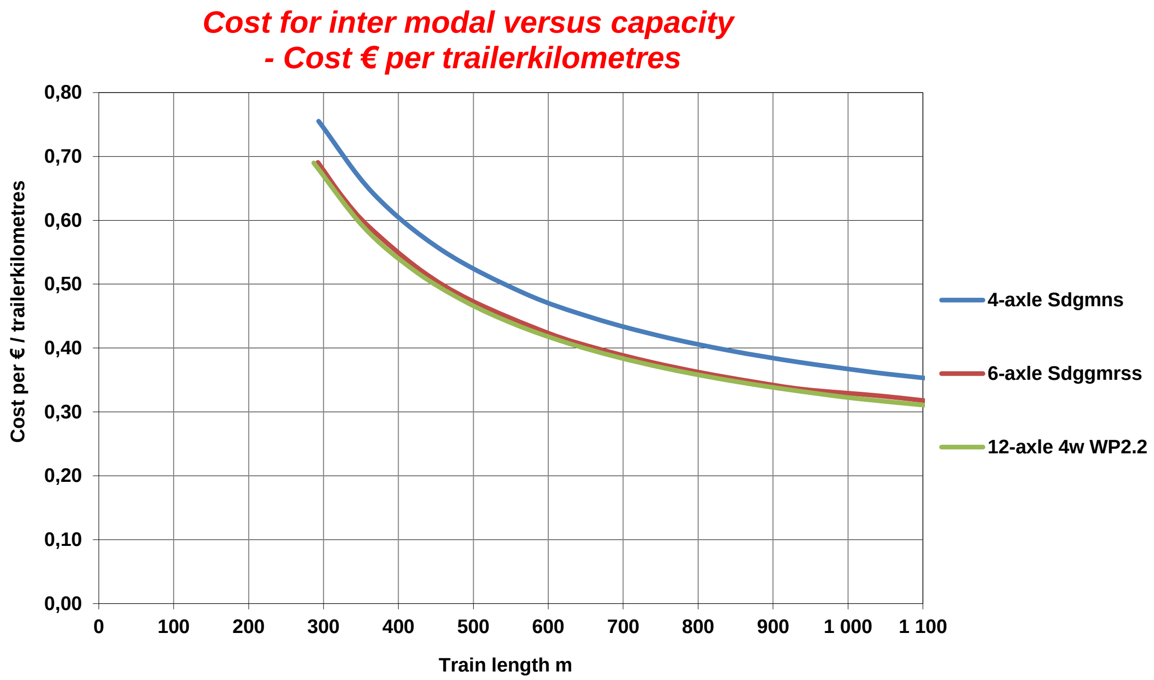


Figure 8.9: Transport cost per TEU-kilometres depending on train length for Inter Modal wagons for liftable trailers. Source: KTH cost calculations.

8.4 Inter modal trailer wagons for non-liftable trailers

The wagon concepts which have been analysed in this section are:

- A 6-axle wagon with Jacob-bogie for 2 trailers "Modalohr"
- A 6-axle bogie wagon with 2 frames and Jacob-bogie for 2 trailers "Megaswing"
- A 4-axle bogie wagon for one truck with semitrailer "Flexiwagon"
- A 16-axle bogie-wagon for 4 trailers "TrailerTrain"

Modalohr is the only wagon which is in regular service today. Megaswing and Flexiwagon exists as prototypes. Trailer Train is a prospect not yet implemented. Modalohr have been coupled together with two waggons and TrailerTrain have here been coupled in 4 wagons but both can be coupled in flexible configurations. Flexiwagon can load the trailer with truck, the other ones are built only for trailers. Modalohr need a special terminal to load, Megaswing and Flexiwagon need no terminal and TrailerTrain need a ramp.

In table 8.10 detailed data from the calculations are shown and in figure 8.11 the main results of improvement in capacity and costs. The 6-axle Sdggmrss for liftable trailer is used as a reference. Wagons for non liftable trailers are mostly more complex and less efficient than wagons for liftable trailers. Modalohr and Megaswing is 6 % more expensive per trailer-kilometre than the wagon for non-liftable trailers but the capacity is approximately the same.

The 4-axle Flexiwaggon is extremely expensive to operate, almost double the cost compared with a wagon for non liftable trailers, but in this case also the truck is on board. The capacity per train-metre is therefore 42 % less.

The most efficient is the 16-axle Trailertrain which increase the capacity per train-metre with 15 % and decrease the cost with 3 % in cost per trailer-kilometre compared with the reference wagon. This is what in US is called “Trailers On Flat Cars” (TOFC) and is dependent of a low floor wagon and very high loading gauge which exists i.e. in Sweden.

In figure 8.12 the cost for the different wagons depending on train length is shown. The differences between the wagons are rather big especially Flexiwaggon compared with the other wagons. The importance filling the trains with wagons and operate long trains is evident.

Please note that the terminal costs are not included and that the advantages with this wagons are that they can handle non-liftable trailers and that is why they are more complex and have higher costs than wagons for liftable trailers. A normal cost for lifting a trailer in a terminal with is 30 € per terminal. In both origin and destination it will be an additional cost of 60 € per trailer. This can be added as a measure for the terminal cost for liftable trailers. If the distance is 1,000 km it will be an additional cost of 0.06 €/trailerkm. If this cost is added to the operating cost for the wagon it will increase the cost with 17 % for a 6-axle Sdggmrss. So there is a marginal for the wagons which not need any complicated terminal handling equipment as the Megaswing, Flexiwaggon and Trailer Train. Modalohr need a rather complicated terminal so may be the cost advantage is not so big but on the other hand it can offer a supply for non liftable trailers.

Table 8.10: Transport costs for Inter Modal wagons for non-liftable trailers. 6-axle Sdggmrss for liftable trailer is reference. Source: KTH cost calculations.

Product	Inter Modal	Non-liftable trailers	984 km	Helsingborg-Duisburg	
Locomotive	4-axle electric 21,0	4-axle electric 21,0	4-axle electric 21,0	4-axle electric 21,0	4-axle electric 21,0
Wagon	6-axle Sdggmrss	6-axle Modalohr UI(	6-axle Megaswing d	16-axle Trailertrain	4-axle Flexiwaggon
Gross ton	2 037	2 199	2 205	2 448	1 829
Length m	737	750	736	732	728
No of locos	1	1	1	1	1
No of wagons	21	21	21	12	24
Operating costs					
€/loco km	8	7,66	7,66	7,66	7,66
€/wagon km	0,32	0,36	0,37	0,70	0,36
€/train km	14	15,27	15,35	16,03	16,29
Capacity					
No of trailers/wagon	2	2	2	4	1
No of trailers/train	42	42	42	48	24
Trailers/Trainmetre	0,057	0,056	0,057	0,066	0,033
Change	0%	-2%	0%	15%	-42%
Cost/Capacity					
Cost € per trailer km	0,34	0,36	0,37	0,33	0,68
Index	100	93	105	103	175
Change	0%	6%	6%	-3%	97%

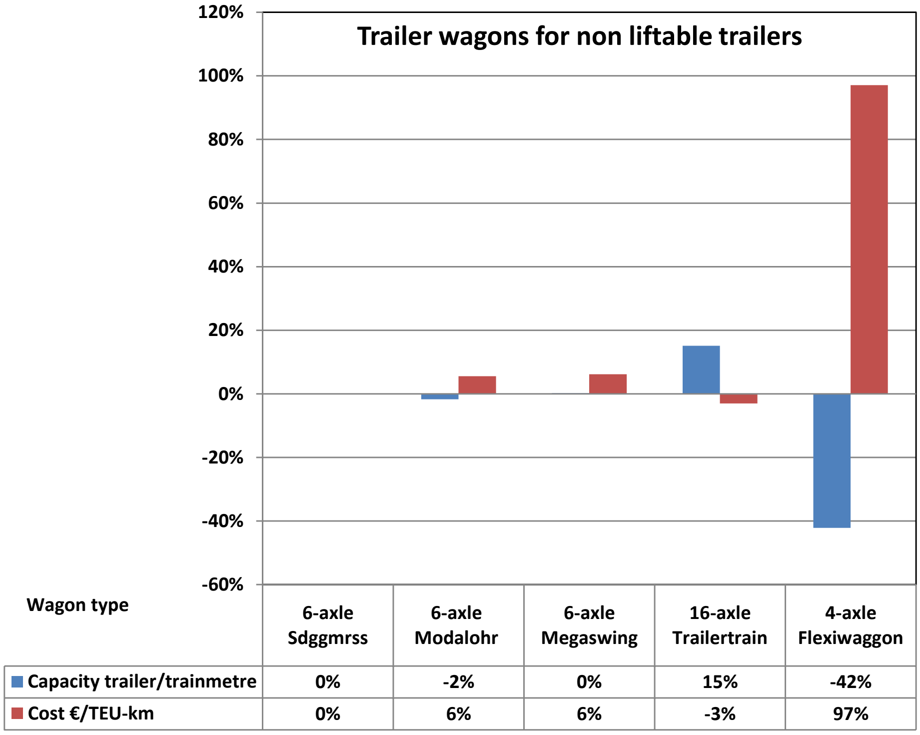


Figure 8.11: Transport cost per TEU-kilometres and capacity in TEU per train-metre for Inter Modal wagons for non-liftable trailers. 6-axle Sdggmrss for liftable trailer is reference. Source: KTH cost calculations.

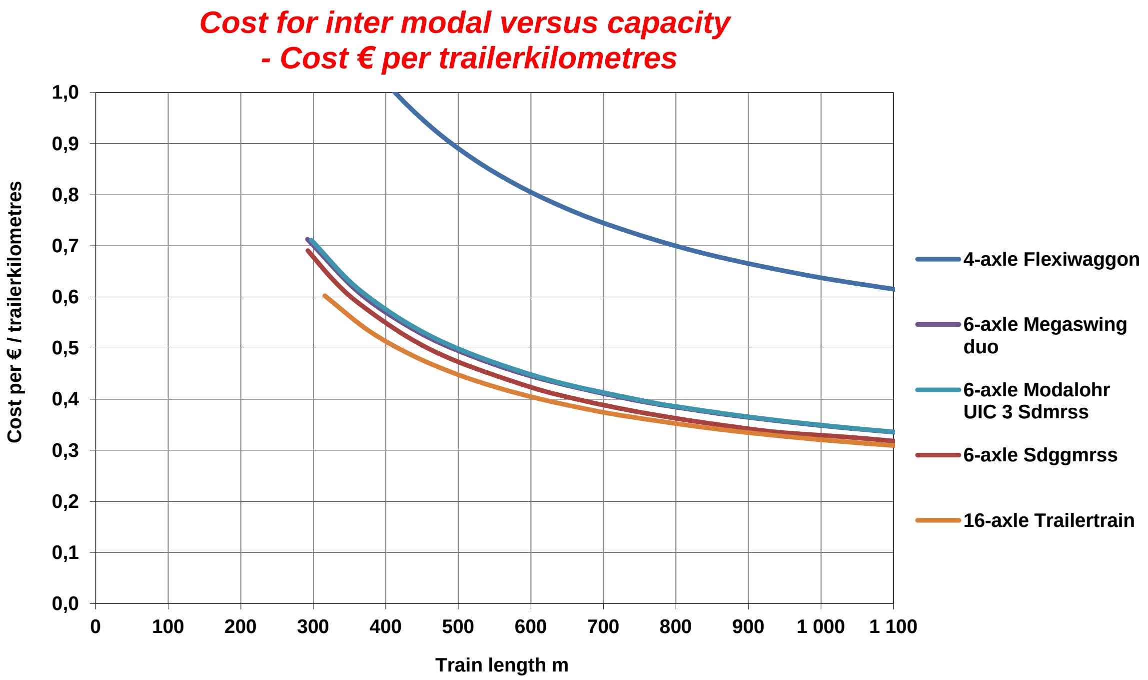


Figure 8.12: Transport cost per TEU-kilometres depending on train length for Inter Modal wagons for non-liftable trailers. 6-axle Sdggmrss for liftable trailer is reference. Source: KTH cost calculations.

8.5 Wagon load car transport wagons

The wagon concepts which have been analysed in this section are:

- A pair-coupled single axle wagon with 4 axles as a reference
- A pair-coupled single axle wagon with 3 axles
- A rake of 6 single axle wagon with 6 axles

The rake of 5 single-axle wagon is the new concept defined in WP.2.2. The other wagons are existing conventional wagons.

In table 8.13 detailed data from the calculations are shown and in figure 8.14 the main results of improvement in capacity and costs. The most efficient is the new 6-axle wagon which is 10 % cheaper per car-kilometre and has 9 % higher capacity per train-metre than the 4-axle reference wagon. The 3-axle wagon has 3 % higher capacity and 4 % lower cost than the 4-axle wagons.

In figure 8.15 the cost for the different wagons depending on train length is shown. The differences between the wagons are not so big. The importance filling the trains with wagons and operate long trains is evident.

Table 8.13: Transport costs and capacity for Car transport wagons. Source: KTH cost calculations.

Wagon Load	Car transport wagor	1007 km	Hallsberg-Maschen
Locomotive	4-axle electric 21,0	4-axle electric 21,0	4-axle electric 21,0
Wagon type	4-axle DB Laaers	3-axle DB Laaeks	6-axle WP 2.2
Gross ton	644	662	594
Max. train length (m)	740	740	740
Actual length (m)	724	734	731
No of locos	1	1	1
No of wagons	23	27	11
Operating costs			
€/loco km	7,89	7,89	8,02
€/wagon km	0,14	0,12	0,26
€/train km	11,04	11,04	10,93
Capacity			
No of cars/wagon	12,70	11,30	29,30
No of cars/train	292	305	322
Cars/Trainmetre	0,40	0,42	0,44
Change	0%	3%	9%
Cost/Capacity			
Cost € per car/km	0,038	0,036	0,034
Index	100	96	90
Change	0%	-4%	-10%

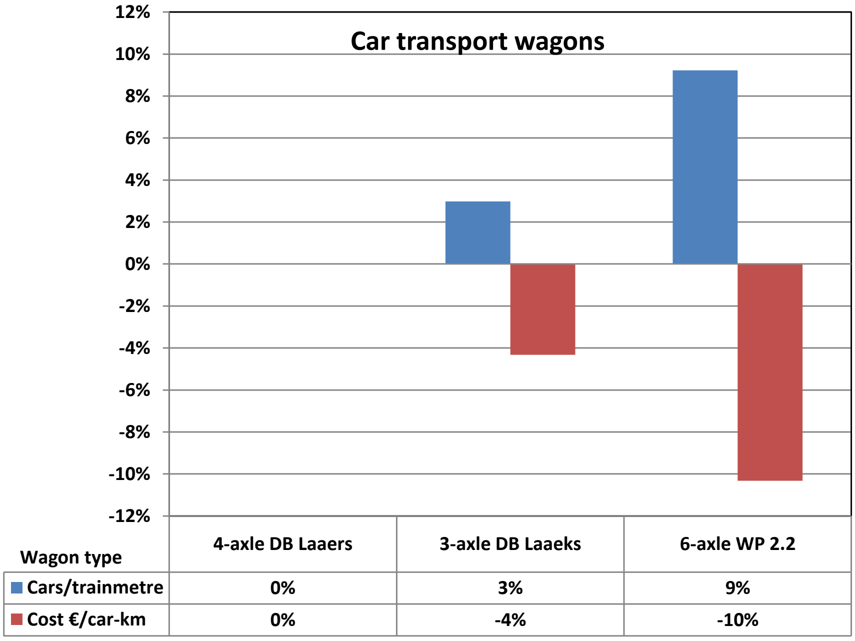


Figure 8.14: Transport cost per car-kilometres and capacity in cars per train-metre for Car transport wagons. Source: KTH cost calculations.

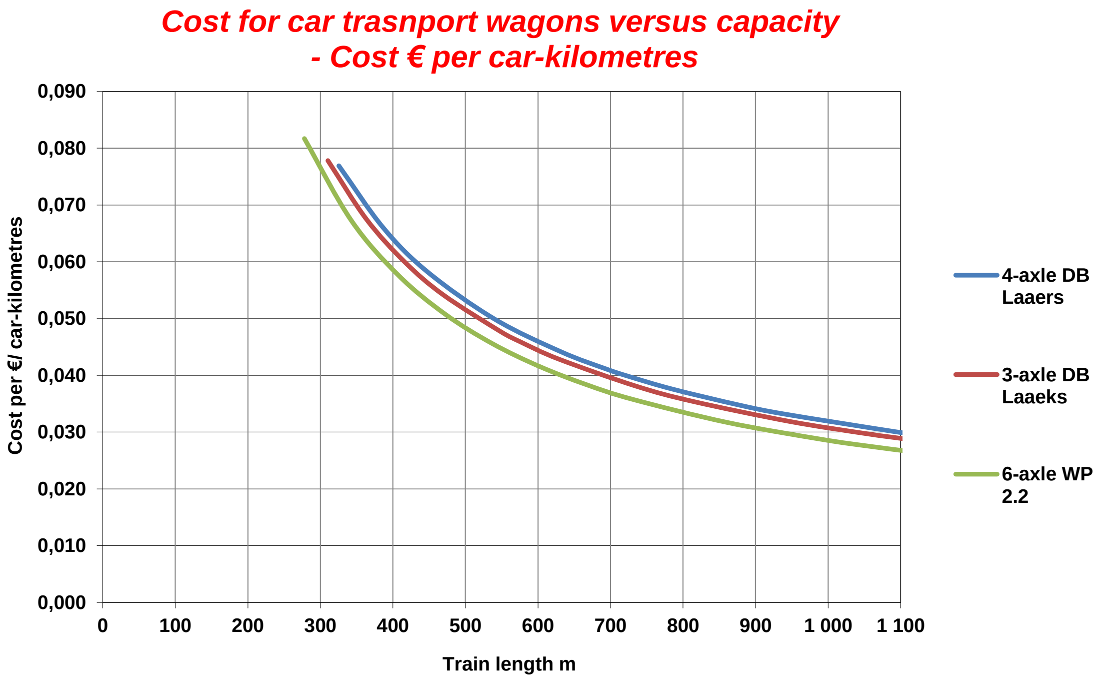


Figure 8.15: Transport cost per car-kilometres depending on train length for car transport wagons. Source: KTH cost calculations.

8.6 Train load steel transport wagons

The most important factor for heavy train load is the axle load. Therefore in this chapter different axle loads are analysed. The wagon concepts which have been analysed in this section are:

- A 4-axle bogie wagon with 20.0 tonnes axle load
- A 4-axle bogie wagon with 22.5 tonnes axle load
- A 4-axle bogie wagon with 25 tonnes axle load
- A 4-axle light-weight bogie wagon with 25 tonnes axle load
- A 4-axle bogie wagon with 30 tonnes axle load

The light weight wagon is the new concept which has been developed in the “green train project” and is assumed to be manufactured of high sustainable steel which is lighter than normal steel. It can load 2 tonnes more than a conventional wagon and has assumed to have 7 % higher investment cost than a conventional wagon. The other ones are existing wagons with different axle loads type Shimms. These wagons are i.e. used for the Swedish steel industry.

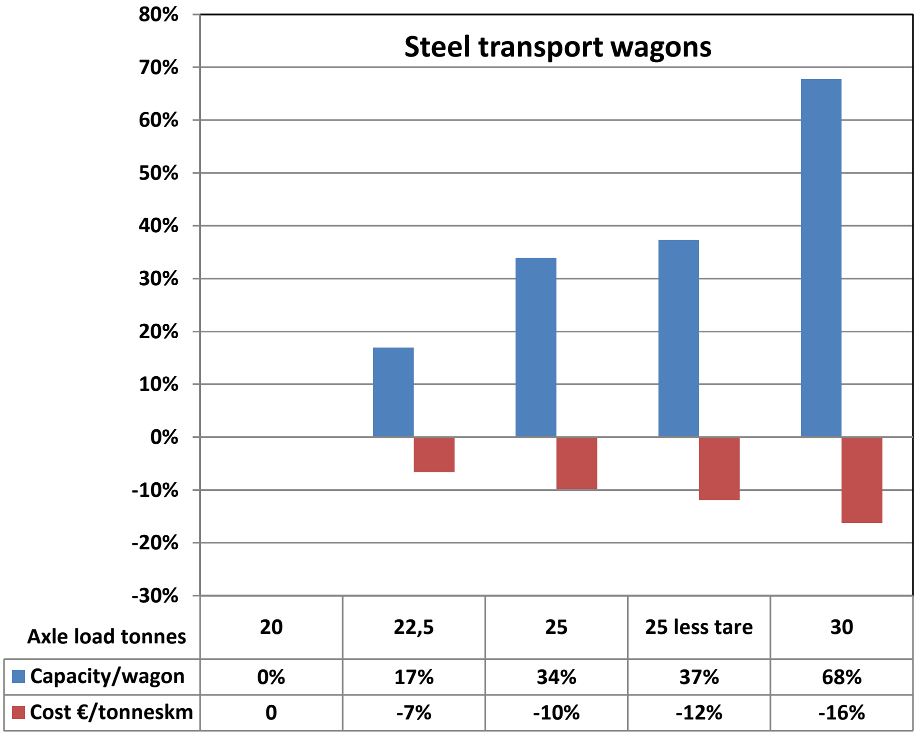
In table 8.16 detailed data from the calculations are shown and in figure 8.17 the main results of improvement in capacity and costs. In this the total train weight has been constant at approximately 3,200 gross tonnes. The maximum train length is 630 metre but this is not critical because all trains are shorter.

The importance of higher axle load is evident. To increase the axle load from 20 to 25 tonnes means 34 % higher capacity per wagon and 10 % decreased cost per net tonnes. A light weight wagon with 25 tonnes axle load can increase the capacity with 37 % and decrease the cost with 12 %. The most efficient is 30 tonnes axle load which is 16 % cheaper per tonnes-kilometre and has 68 % higher capacity per train-metre than the 20 tonnes axle load reference wagon.

In figure 8.18 the cost for the different wagons depending on train length is shown. The differences between the wagons with different axle load are very big. The importance filling the trains with wagons and operate heavy trains is also evident.

Table 8.16: Transport costs and capacity for steel transport wagons with different axle load. Source: KTH cost calculations.

Product	Train Load	Axle load	999 km	Luleå-Borlänge	
Locomotive	4-axle electric 21,0	4-axle electric 21,0	4-axle electric 21,0	4-axle electric 21,0	4-axle electric 21,0
Wagon type - axle loa	Shimms 20	Shimms 22,5	Shimmns 25	Shimmns 25 light	Shimmns 30
Gross tonnes	3 200	3 240	3 200	3 200	3 240
Net tonnes	2 360	2 484	2 528	2 592	2 673
Max. train length (m)	630	630	630	630	630
Actual length (m)	557	509	461	461	438
No of locos	2	2	2	2	2
No of wagons	40	36	32	32	27
Operating costs					
€/loco km	7,94	7,94	7,94	7,94	7,94
€/wagon km	0,23	0,24	0,26	0,26	0,29
€/train km	17,00	16,61	16,22	16,26	15,82
Capacity					
Axle load (tonnes)	20	22,5	25	25 less tare	30
Capacity/wagon (tonn	59	69	79	81	99
Change	0%	17%	34%	37%	68%
Cost/Capacity					
Cost/nettonkm	0,19	0,17	0,17	0,16	0,16
Index	100	93	90	88	84
Change	0%	-7%	-10%	-12%	-16%



Axle load tonnes	20	22,5	25	25 less tare	30
🟦 Capacity/wagon	0%	17%	34%	37%	68%
🟥 Cost €/tonneskm	0	-7%	-10%	-12%	-16%

Figure 8.17: Transport cost per car-kilometres and capacity in cars per train-metre for steel transport wagons with different axle load. Source: KTH cost calculations.

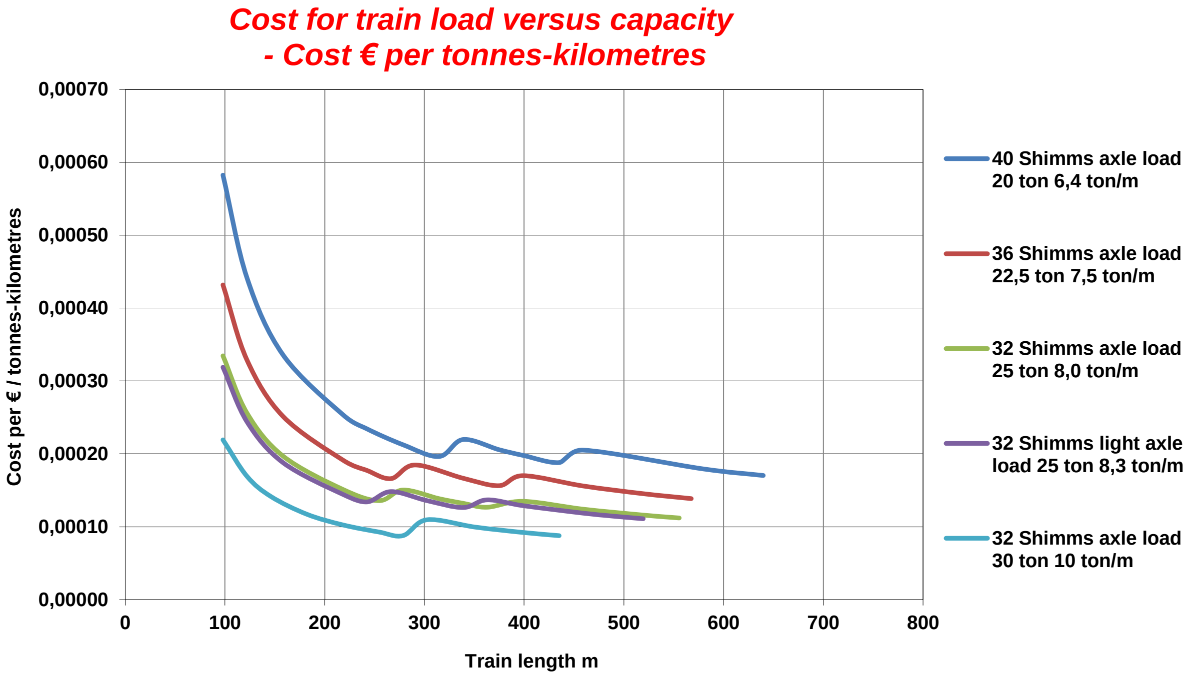


Figure 8.18: Transport cost per car-kilometres depending on train length for steel transport wagons with different axle load. Source: KTH cost calculations.

8.7 Wagon load high cube wagons

The wagon concepts which have been analysed in this section are:

- A 6-axle bogie wagon with Jacob-bogie as a reference
- A 4-axle bogie high volume wagon VEL-wagon for wagon load, a new concept
- A 4-axle US bogie-wagon Jumbo box car

The 6-axle bogie-wagon is an existing type Haimmrs and used for manufactured car parts. The 4-axle bogie-wagon was an idea in the VEL-wagon project not yet implemented. The US box car is to compare what can be achieved with quite different infrastructure performance.

In table 8.19 detailed data from the calculations are shown and in figure 8.20 the main results of improvement in capacity and costs.

The 4-axle VEL-wagon load wagon can increase the capacity with 9 % and reduce the cost with 19 % compared with the 6-axle Haimmrs-wagon. The big advantage of a high gauge is shown by the US box-car which has 73 % higher capacity and 40 % lower cost per M^3 than the Haimmrs-wagon.

In figure 8.21 the cost for the different wagons depending on train length is shown. The differences between the wagons with different volume are very big. The importance filling the trains with wagons and operate heavy trains is evident.

Table 8.19: Transport cost and capacity for high cube wagons. Source: KTH cost calculations.

Wagon Load	High cube wagons	1007 km	Hallsberg-Maschen
Locomotive	4-axle electric 21,0	4-axle electric 21,0	4-axle electric 21,0
Wagon type - axle load	Haimmrs	VEL-WL	US jumbo
Gross tonnes	944	840	1 250
Max. train length (m)	750	750	750
Actual length (m)	741	740	732
No of locos	1	1	1
No of wagons	28	28	27
Operating costs			
€/loco km	7,89	7,89	8,02
€/wagon km	0,19	0,13	0,22
€/train km	13,24	11,61	13,83
Capacity			
Capacity/wagon (m3)	180	196	323
Capacity/train (m3)	5040	5488	8721
Change	0%	9%	73%
Cost/Capacity			
Cost/m3	0,0026	0,0021	0,0016
Index	100	81	60
Change	0%	-19%	-40%

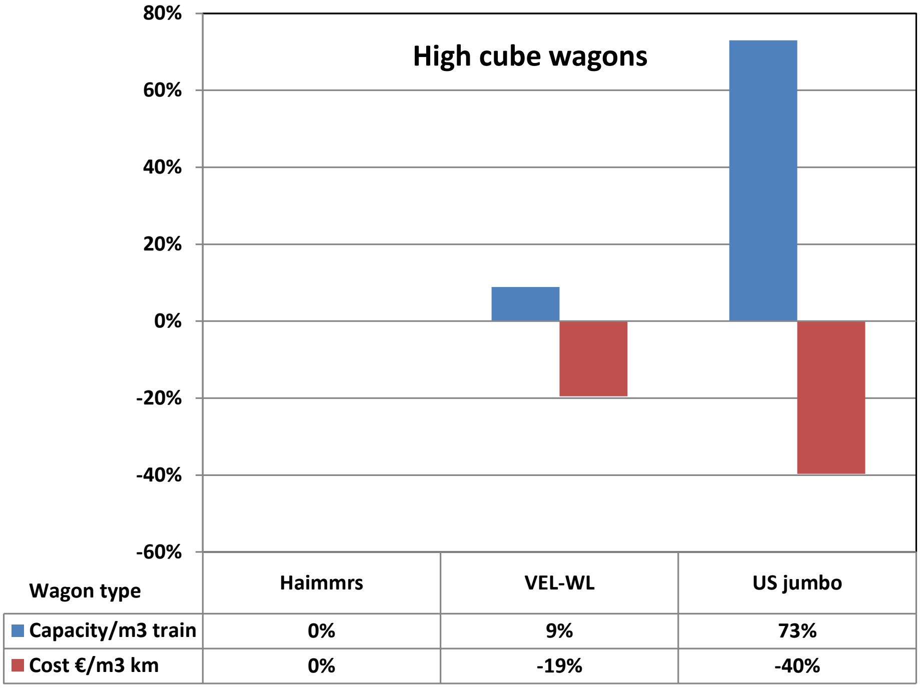


Figure 8.20: Transport cost per m3-kilometres and capacity in m3 per train for high cube wagons. Source: KTH cost calculations.

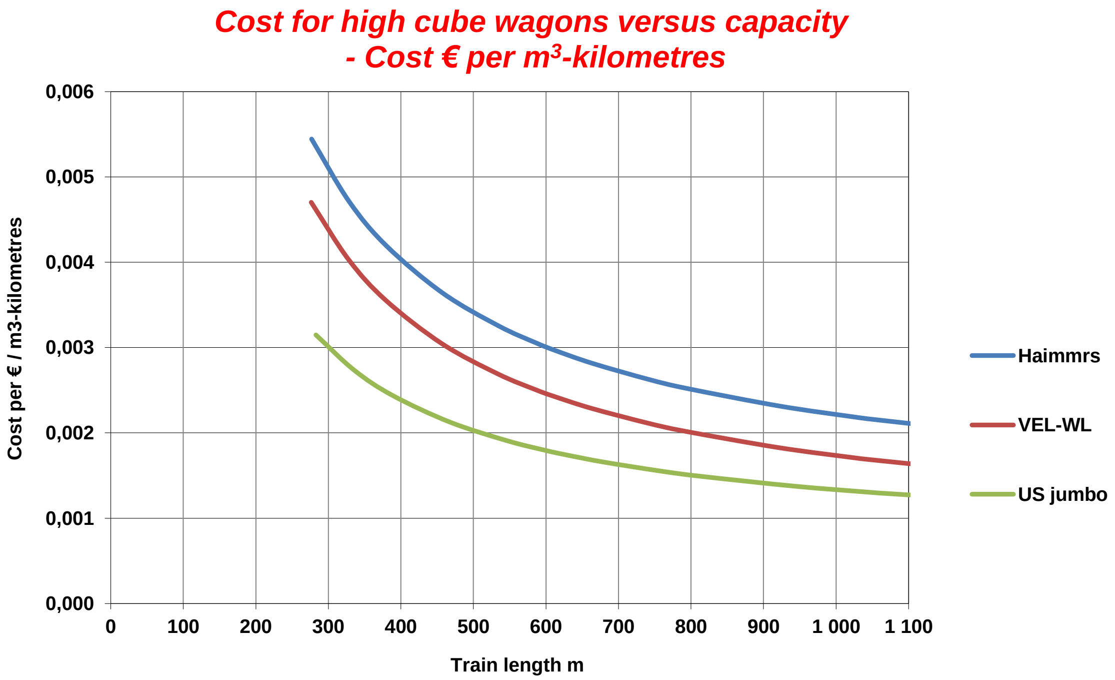


Figure 8.21: Transport cost per car-kilometres depending on train length for high cube wagons. Source: KTH cost calculations.

Literature

[1] Capacity4Rail Project SP2, Deliverable 21.2: Requirements toward the freight system of 2030/2050. Edited by Bo-Lennart Nelldal 31/01/2017.

[2] Godstransporter 2014-2030-2050 – Analys av godsflöden, järnvägens produkter och rangerbangårdar. Bo-Lennart Nelldal, Jakob Wajsman (Trafikverket). KTH rapport 2015 TRITA-TSC RR 15-003.

[3] Railway capacity analysis - Methods for simulation and evaluation of timetables, delays and infrastructure. Anders Lindfeldt, Doctoral Thesis, KTH, Stockholm 2015, TRITA-TSC-PHD 15-002.

[4] Capacity4Rail Project SP2 WP 2.2 MS 15 Scenarios of Development of new rail freight vehicles. Bo-Lennart Nelldal, 14/02/2017.

[5] System analysis of an introduction of HCVs on road in Sweden, Adell, E et al., Department of Technology and Society, Lund University Report 2016-10-25.

Table 34. Rail Freight Traffic Mix for Baseline (from 2015 to 2019)

Section		Baseline (from 2015 to 2019)					Baseline (from 2020)					C4R Scenario 1 (All)				
		Train Load	Wagon Load	IM Container	IM Trailer	WL Feeder	Train Load	Wagon Load	IM Container	IM Trailer	WL Feeder	Train Load	Wagon Load	IM Container	IM Trailer	WL Feeder
S5	Stockholm - Katrineholm	12%	11%	24%	47%	5%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S5	Katrineholm-Hallsberg	15%	14%	32%	31%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S5	Katrineholm-Norrköping	22%	13%	30%	29%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S5	Norrköping-Mjölby	20%	19%	28%	27%	6%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S5	Hallsberg - Degerön	23%	53%	12%	6%	5%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S6	Degerön - Mjölby	23%	53%	12%	6%	5%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S5	Mjölby - Nässjö	19%	37%	8%	30%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S5	Nässjö-Alvesta	19%	37%	8%	30%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S6	Alvesta-Lund	19%	37%	8%	30%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S5	Lund - Malmö	19%	37%	8%	30%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S6	Oslo-Halden	14%	26%	30%	29%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S6	Halden-Öxnered	25%	23%	26%	25%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S6	Öxnered-Göteborg	24%	29%	25%	16%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S7	Göteborg - Kungsbacka	26%	31%	9%	26%	8%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S7	Kungsbacka-Ängelholm	26%	31%	9%	26%	8%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S7	Ängelholm - Kävlinge via Helsingborg	23%	21%	24%	23%	10%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S7	Ängelholm - Kävlinge via Åstorp	14%	13%	30%	29%	13%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S7	Kävlinge - Lund	14%	13%	30%	29%	13%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S7	Kävlinge - Malmö	14%	13%	30%	29%	13%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S8	Malmö - Trelleborg	9%	8%	10%	65%	8%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S9	Malmö - København	20%	25%	28%	27%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

TABLE 35. RAIL FREIGHT TRAFFIC MIX FOR BASELINE (FROM 2020)

		Baseline (from 2015 to 2019)					**Baseline (from 2020)**					**C4R Scenario 1 (All)**				
Section		Train Load	Wagon Load	IM Container	IM Trailer	WL Feeder	Train Load	Wagon Load	IM Container	IM Trailer	WL Feeder	Train Load	Wagon Load	IM Container	IM Trailer	WL Feeder
S5	Stockholm - Katrineholm	0%	0%	0%	0%	0%	12%	8%	27%	49%	4%	0%	0%	0%	0%	0%
S5	Katrineholm-Hallsberg	0%	0%	0%	0%	0%	16%	11%	36%	32%	5%	0%	0%	0%	0%	0%
S5	Katrineholm-Norrköping	0%	0%	0%	0%	0%	22%	10%	34%	30%	5%	0%	0%	0%	0%	0%
S5	Norrköping-Mjölby	0%	0%	0%	0%	0%	21%	14%	32%	28%	5%	0%	0%	0%	0%	0%
S5	Hallsberg - Degerön	0%	0%	0%	0%	0%	27%	46%	16%	7%	5%	0%	0%	0%	0%	0%
S6	Degerön - Mjölby	0%	0%	0%	0%	0%	27%	46%	16%	7%	5%	0%	0%	0%	0%	0%
S5	Mjölby - Nässjö	0%	0%	0%	0%	0%	21%	31%	9%	34%	6%	0%	0%	0%	0%	0%
S5	Nässjö-Alvesta	0%	0%	0%	0%	0%	21%	31%	9%	34%	6%	0%	0%	0%	0%	0%
S6	Alvesta-Lund	0%	0%	0%	0%	0%	21%	31%	9%	34%	6%	0%	0%	0%	0%	0%
S5	Lund - Malmö	0%	0%	0%	0%	0%	21%	31%	9%	34%	6%	0%	0%	0%	0%	0%
S6	Oslo-Halden	0%	0%	0%	0%	0%	15%	20%	34%	31%	0%	0%	0%	0%	0%	0%
S6	Halden-Öxnered	0%	0%	0%	0%	0%	26%	18%	30%	27%	0%	0%	0%	0%	0%	0%
S6	Öxnered-Göteborg	0%	0%	0%	0%	0%	25%	23%	29%	17%	6%	0%	0%	0%	0%	0%
S7	Göteborg - Kungsbacka	0%	0%	0%	0%	0%	28%	25%	11%	29%	6%	0%	0%	0%	0%	0%
S7	Kungsbacka-Ängelholm	0%	0%	0%	0%	0%	28%	25%	11%	29%	6%	0%	0%	0%	0%	0%
S7	Ängelholm - Kävlinge via Helsingborg	0%	0%	0%	0%	0%	24%	16%	27%	24%	8%	0%	0%	0%	0%	0%
S7	Ängelholm - Kävlinge via Åstorp	0%	0%	0%	0%	0%	15%	10%	34%	31%	10%	0%	0%	0%	0%	0%
S7	Kävlinge - Lund	0%	0%	0%	0%	0%	15%	10%	34%	31%	10%	0%	0%	0%	0%	0%
S7	Kävlinge - Malmö	0%	0%	0%	0%	0%	15%	10%	34%	31%	10%	0%	0%	0%	0%	0%
S8	Malmö - Trelleborg	0%	0%	0%	0%	0%	9%	6%	11%	67%	6%	0%	0%	0%	0%	0%
S9	Malmö - København	0%	0%	0%	0%	0%	21%	19%	32%	28%	0%	0%	0%	0%	0%	0%

Table 36. Rail Freight Traffic Mix for Scenario 1 after 2030. We assumed longer trains would make up 50% of the traffic from 2030.

		Baseline (from 2015 to 2019)					**Baseline (from 2020)**					**C4R Scenario 1 (All)**				
Section		Train Load	Wagon Load	IM Container	IM Trailer	WL Feeder	Train Load	Wagon Load	IM Container	IM Trailer	WL Feeder	Train Load	Wagon Load	IM Container	IM Trailer	WL Feeder
S5	Stockholm - Katrineholm	0%	0%	0%	0%	0%	6%	4%	13%	24%	2%	6%	4%	13%	24%	2%
S5	Katrineholm-Hallsberg	0%	0%	0%	0%	0%	8%	6%	17%	16%	3%	8%	6%	17%	16%	3%
S5	Katrineholm-Norrköping	0%	0%	0%	0%	0%	11%	5%	16%	15%	3%	11%	5%	16%	15%	3%
S5	Norrköping-Mjölby	0%	0%	0%	0%	0%	10%	8%	15%	14%	3%	10%	8%	15%	14%	3%
S5	Hallsberg - Degerön	0%	0%	0%	0%	0%	13%	24%	7%	3%	2%	13%	24%	7%	3%	2%
S6	Degerön - Mjölby	0%	0%	0%	0%	0%	13%	24%	7%	3%	2%	13%	24%	7%	3%	2%
S5	Mjölby - Nässjö	0%	0%	0%	0%	0%	10%	16%	4%	16%	3%	10%	16%	4%	16%	3%
S5	Nässjö-Alvesta	0%	0%	0%	0%	0%	10%	16%	4%	16%	3%	10%	16%	4%	16%	3%
S6	Alvesta-Lund	0%	0%	0%	0%	0%	10%	16%	4%	16%	3%	10%	16%	4%	16%	3%
S5	Lund - Malmö	0%	0%	0%	0%	0%	10%	16%	4%	16%	3%	10%	16%	4%	16%	3%
S6	Oslo-Halden	0%	0%	0%	0%	0%	7%	11%	16%	15%	0%	7%	11%	16%	15%	0%
S6	Halden-Öxnered	0%	0%	0%	0%	0%	13%	10%	14%	13%	0%	13%	10%	14%	13%	0%
S6	Öxnered-Göteborg	0%	0%	0%	0%	0%	12%	12%	14%	8%	3%	12%	12%	14%	8%	3%
S7	Göteborg - Kungsbacka	0%	0%	0%	0%	0%	14%	14%	5%	14%	3%	14%	14%	5%	14%	3%
S7	Kungsbacka-Ängelholm	0%	0%	0%	0%	0%	14%	14%	5%	14%	3%	14%	14%	5%	14%	3%
S7	Ängelholm - Kävlinge via Helsingborg	0%	0%	0%	0%	0%	12%	9%	13%	12%	4%	12%	9%	13%	12%	4%
S7	Ängelholm - Kävlinge via Åstorp	0%	0%	0%	0%	0%	7%	6%	16%	15%	6%	7%	6%	16%	15%	6%
S7	Kävlinge - Lund	0%	0%	0%	0%	0%	7%	6%	16%	15%	6%	7%	6%	16%	15%	6%
S7	Kävlinge - Malmö	0%	0%	0%	0%	0%	7%	6%	16%	15%	6%	7%	6%	16%	15%	6%
S8	Malmö - Trelleborg	0%	0%	0%	0%	0%	5%	4%	5%	33%	4%	5%	4%	5%	33%	4%
S9	Malmö - København	0%	0%	0%	0%	0%	10%	10%	15%	14%	0%	10%	10%	15%	14%	0%