C4R

Capacity for Rail

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

Novel rail freight vehicles (Intermediate)

Submission date: 03/10/2017

Deliverable 22.2

Lead contractor for this deliverable:

- NEWOPERA

Project coordinator

- International Union of Railways, UIC

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1 Executive Summary

WP22 is aiming to propose solutions to enhance the efficiency of Rail Freight transport. At the beginning a large forwarder operating long distance combined trains across Europe and a Car carrier operating a fleet of more than 3500 wagons involved in multimodal logistics across Europe and being also an ECM for other wagon operators have expressed their most urgent needs to increase their efficiency by reducing their operating costs while improving the quality of service. The tools that this work package wanted to develop was to increase the usable length of a standard train with new wagon designs having a lower LCC. At the same time improving the asset rotation with synchronous braking of all wagons could have reduced the wear and tear of the new composite brake blocks aiming at reducing noise. Several designs have been studied for car carrier wagons reaching 5 bodies with 6 axels for an overall length of around 62m. For container traffics two ideas have been studied. The first one was to introduce in a standard train composed of wagons capable to carry 40' containers or 40' plus 20' containers a partial flexibility to transport a third of the containers of 45' without lengthening the trains and with minimal changes on the wagons. The second idea studied was a new design of a 5 bodies wagon with 6 bogies for an overall length of around 72m. This solution was aiming to reduce the number of bogies and hence the maintenance cost. The third idea was to develop the same concept for transport of craneable semitrailers with a 4 bodies wagon with 6 bogies for an overall length of around 67M. Each of these solutions were studied successfully in term of stability with the mathematical programs of KTH. The cost of these new designs were estimated by NTnetAB and the operational efficiencies calculated when possible or estimated according to expert experience. The impact in terms of temperature reduction with synchronous braking showed a significant decrease on the test benches of Knorr Bremse. Unfortunately new braking methodologies by applying successively strong braking followed by a release have reduced the temperature reached by the blocks and the wheel treads in a zone where the impact of the synchronous braking would not bring significant maintenance cost reduction and damage reduction. For the new wagon designs the cost benefit analysis show interesting progress for the car carrier wagon and the container wagon but not for the pocket wagons. The flexibility of putting a third of the number of container with a length of 45' without lengthening the train may be very promising. Finally an extremely promising field is to reduce significantly the preparation time before the departure of the train with the introduction of an EOT (End Of Train) device. Some final work has been endorsed by Knorr Bremse aiming at analyzing the various possibilities to bring energy to the wagons either to support the Electro-Pneumatic braking and/or to feed the various sensors detectors increasing the safety and allowing to install a predictive maintenance in order to increase the reliability. The final market segment targeted by this research was the possibility to bring energy to reefer containers in a way where no autonomous diesel group would be working in long tunnels. Past experience has shown that this may create a risk which could be avoided in this way if justified economically.

The second important field researched by Knorr Bremse was the communication field. The future freight wagon will have to be connected in order to bring sensitive, up to date and accurate information on the wagon status and on the cargo status to interested stakeholders. This research is linked to the possibility to bring energy by cable to the wagon from the locomotive, the cable carrying also a bus of information. The analysis of the problem was to be done keeping in mind the problems emerging by the progressive deployment of whatever technology in term of hardware equipment. The KB research detailed here under in the deliverables has two chapters describing the various possibilities.

Finally a short consultation of various stakeholders (RUs, IMs, Wagon owners, shippers) handled by Newopera on the basis of direct interviews has brought support to the cost benefit analysis of the various innovations described in this deliverable. The report was also updated by Newopera with the last innovation of the IoT technologies and the latest LPWA communication solutions extremely low in term of energy consumption for limited data transfer and less accurate for positioning before treatment by integrated algorithms. The financial evaluations for the cost benefit analysis have been performed by Newopera in close collaboration with stakeholders involved in the development of such innovations. The benefits of the IoT enables significant progress for the future freight train in terms of reliability, competitiveness and accuracy of information transferred to other participants of complex supply chains.

Roadmaps for implementing certain innovations of this deliverable was yet to be analyzed to define a timing of introduction and the way to have a quick market uptake.

This task has been performed by Newopera on three flows of traffics of finished cars built in Czech Republic and sent by the Port of Koper. Consultations made with the partner STVA which could not continue to participate to the project has however enabled to understand the decision process to introduce innovations in a very competitive market.
The cost benefit analysis made at the end of the project shows that some basic operational innovations and relatively cheap equipments bring significant results which should create a short term market uptake. This analysis should be pursued with a direct consultation of the IMs concerned which were not partners of the project to assess the acceptance of the operational suggestions made in the deliverable as many works are currently being undertaken on the itinerary while the published informations are of 2012 .

2 Background and Objectives of WP2.2: Novel rail freight vehicles

2.1 Fixing the functional targets

The first step of the work in this deliverable was to analyze the customers' demands which were to be satisfied two main customers were involved in that work:

- A large intermodal forwarders (Van Dieren) using full trains crossing Europe from Sweden to Italy via Duisburg in Germany

- A major automotive multimodal logistics operator (STVA) owning 4500 rail cars for finished vehicles, operating fleet of trucks carrying vehicles , managing terminals for car storage and cars adaptation to national standards and being ECM(entity in charge of maintenance) for several large fleets of wagons of different types.

For both of them the main needs were reliability and cost reduction.

At the same time the rail community is facing new stringent rules in the field of noise reduction having a significant impact on the cost of daily wagon utilization.

Basically the main conclusions of this first analysis were simple:

- Find new designs to reduce the dead weight, to increase the usable length of the wagons within the overall length accepted by the Infrastructure managers and without reducing the safety at acceptable speed limits.

- Find solutions that will give more flexibility to the wagons to carry different types of loads specifically in the field of intermodal wagons.

- Find solutions that could reduce the costs created by the new solutions reducing rail noise and which could globally reduce the maintenance costs.

- Find solutions to improve the train maneuverability in terms of braking and releasing the brakes.

In the limited scope of the C4R project linked to the volume of resources attributed to this work package the objective was to imagine the solution, to check its technical feasibility, to assess its impact on the parameters characterizing an improvement on the items listed here above, to assess its safety or to define the operational constraints to be respected in order to maintain the safety level, to estimate the cost of the solution (on the basis of an industrial production) and finally to perform a limited cost benefit analysis in this first part of WP22.

In a second part of the work which will be in the final deliverable, the cost benefit analysis will have to be extended to the train in its environment taking into account its insertion in the traffic, a road map for its introduction in the market, the consequences on the other traffics if any, the impact on the other logistics operations and a possible way to share the benefits among the actors to ensure an alignment of the interests to develop and introduce such solutions.

2.2 From the functional targets to the technological proposals

a.   Gaining usable length in a given maximum train length

In a train the non-usable length is constituted by the buffers between the wagons. This is necessary if you frequently need to decouple the wagons during your operations. The obvious solution partially

applied on certain trains is to introduce draw bars between the wagons. The inconvenience is to have a risk of losing huge time if you have a technical problem on one wagon in a set of multiple wagons. You may be obliged to withdraw a full set of wagon linked by draw bars to ensure rapidly the continuity of the service. So either you have a spare set available or you must change your maintenance methodology to switch to predictive maintenance which is a point which will be dealt further.

The solution has been studied for two different cases: light automotive transport and heavy intermodal transport.

- In the first case a 6 axel car design for transport of finished vehicles has been drawn according to the scheme under:
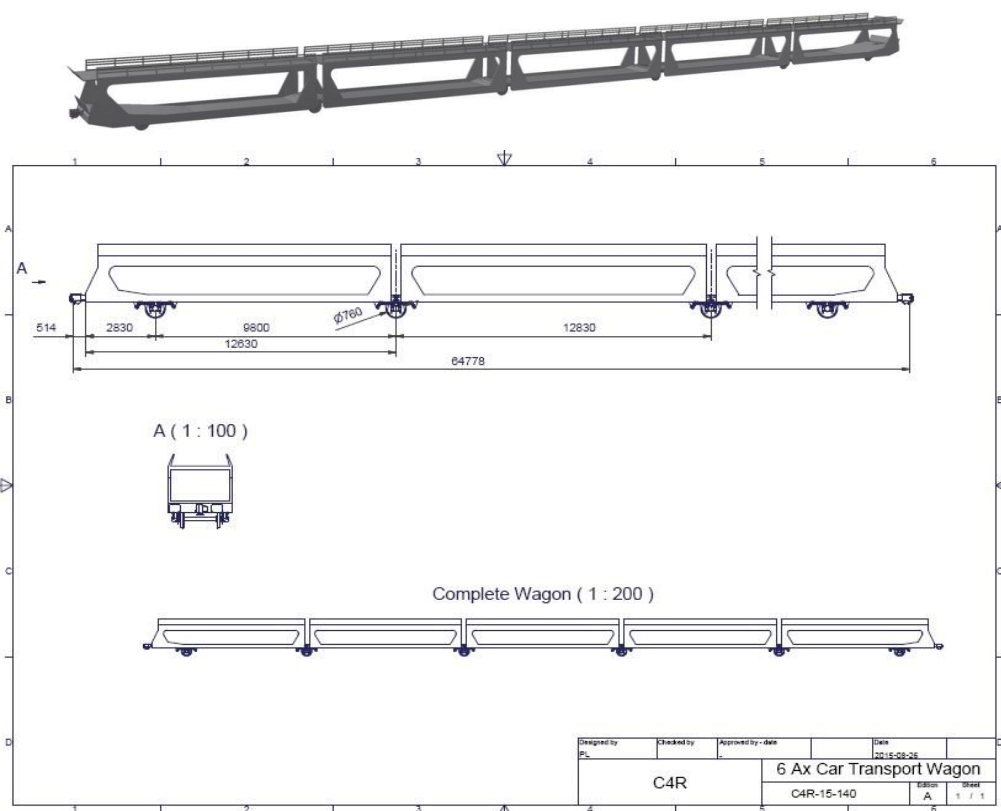
Figure 1: 6 axel car design for transport of finished vehicles. - Source: Ntnet AB and KTH

This design elaborated by Ntnet AB with certain variables has been studied by KTH Royal institute of Technology to check its stability within certain speed limits. Of course this solution is only compatible with light cargo.

- A second solution has been designed for intermodal transport where the weight of the cargo is significantly higher. It is a 12 axel-car design/

Figure 2: 12 axel car design for containers or swap bodies. –Source: NTnet AB and KTH

To keep the carrying capacity despite the reduction of the number of axels a new structure has been completely design to reduce the weight of the structure.
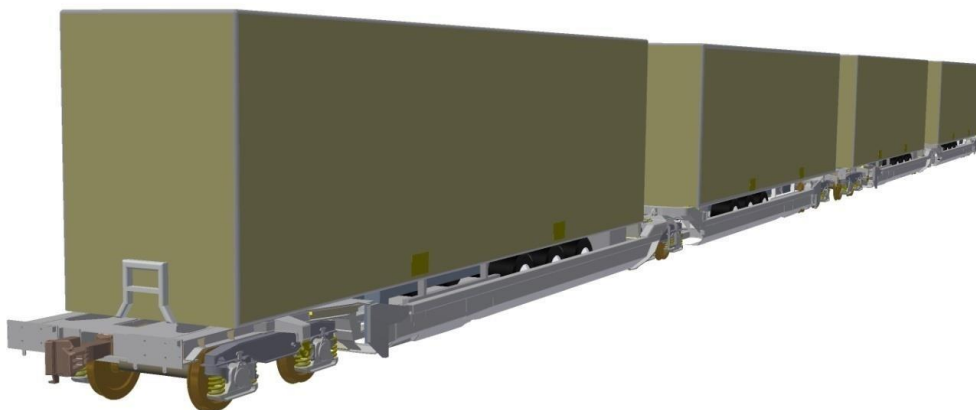
Figure 3: 12 axel car design for semitrailers. –Source: NTnet AB and KTH

The first drawing is for containers or swap bodies and the second drawing is for semitrailers.
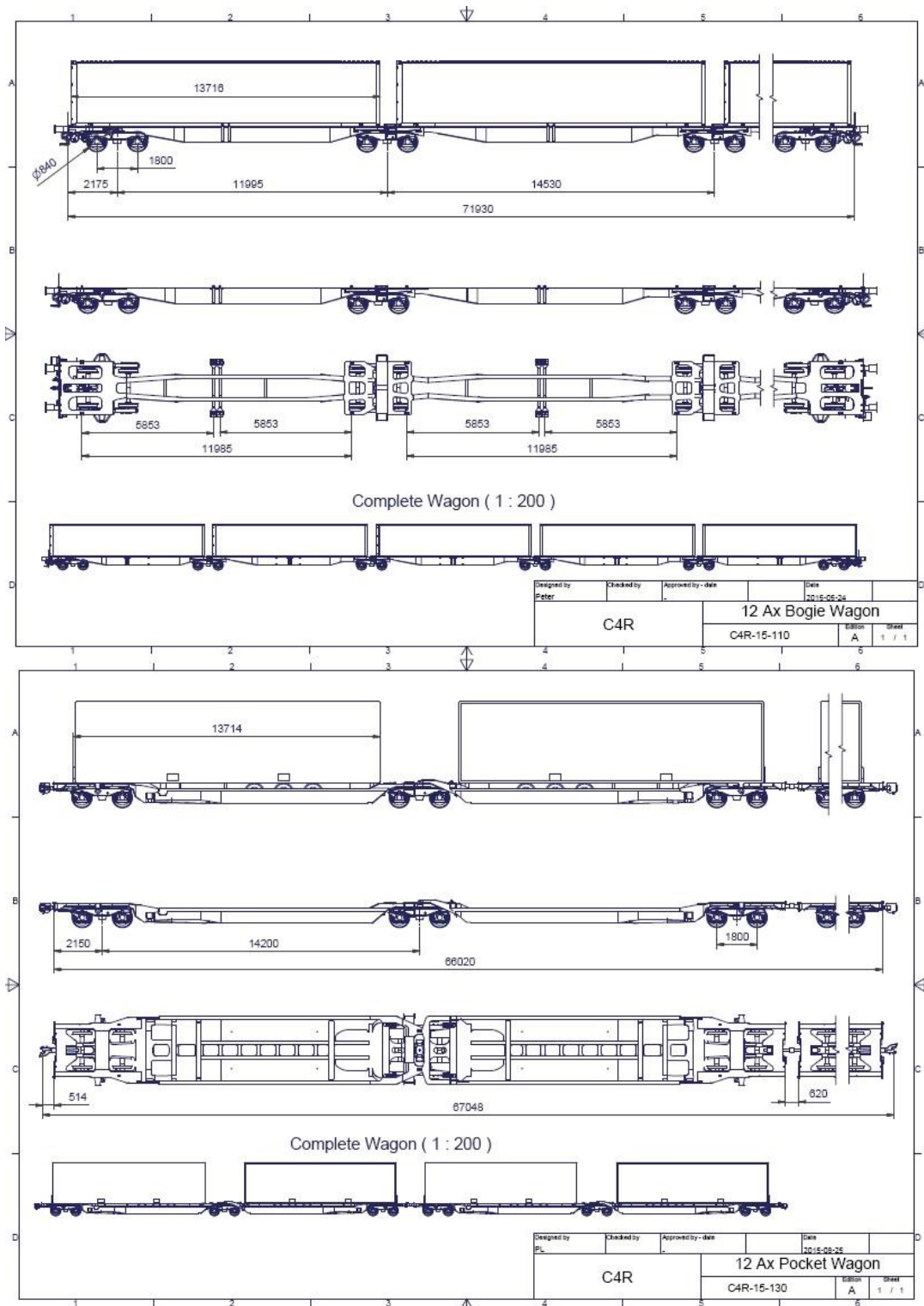
Figure 4: 12 axel bogie wagon. - Source NTnet AB and KTH

b.   Gaining flexibility in transport of different intermodal units.

Huge traffics are arriving in ports from overseas countries. They are then distributed by trains to far destinations. For productivity reasons 45' containers are becoming more frequent in such traffics. Repositioning of containers are not in general done by the port of entrance and it is frequently necessary to have the capacity of transporting some 45'containers on trains full of 20' and or 40' containers. The possible solution is to have systematically 45' instead of 40' capacity on each wagon. The immediate consequence is that every 8 th wagon you have lost a 40' container carrying capacity which is a serious penalization of 12.5% on a train of 720m of wagons with an allocation of 30m for the locomotive.

The idea proposed is to extend on both ends of the wagon the platform over the buffers by 2.5'. This of course does not leave the Bern rectangle which is necessary for the safety of the staff when decoupling wagons during the operation. The proposed solution is to create non de-couplable triple wagons where the middle one will be extended over buffers by 2.5' at each end. This gives a capacity of 17 containers of 45' on 51 wagons for 40' containers without extending the overall train length. The inconvenience is the risk of taking out 3 wagons if there is a technical problem which suggest to switch also to predictive maintenance.
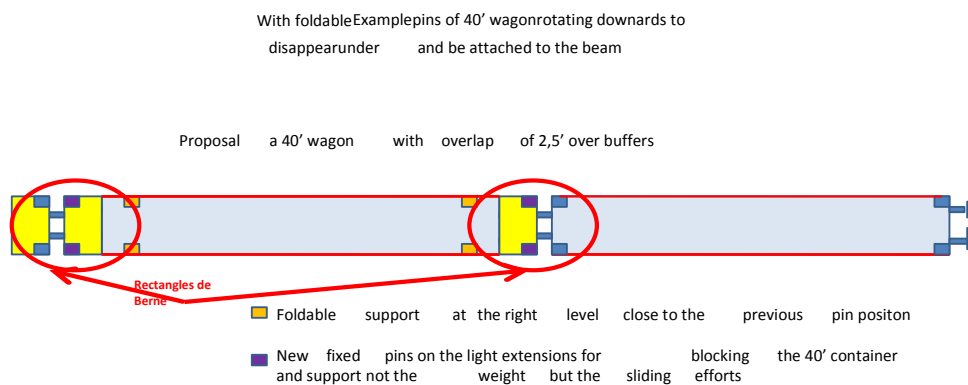
Figure 5: 40' wagon proposed. - Source: Newopera

c. Costs reduction in maintenance of new brake shoes aiming to reduce noise and more generally in maintenance.

Reduction of rail noise is necessary for an improved acceptability of rail freight transport. Two types of noise are generated: the general rolling noise and the noise generated when the train is braking. The second noise is the most aggressive one and lots of studies have been aiming at finding a type of shoe having a significant noise reduction effect. Two types of brake blocks have been experimented K-blocks and LL-Blocks.

K-Blocks are much more costly than cast iron blocks and need a modification of wagons which braking system is not equipped with auto-variable. More over certain types of KBlocks are very aggressive with the wheels which have to be reworked more frequently.

LL-blocks have the advantage not to need the installation of the costly auto-variable system but they are much more costly that the cast iron blocks and are also very aggressive with the wheel implying a more frequent reworking.

The research path adopted in C4R was to try to reduce the braking effort between the shoe and the wheel to try to reduce the wear and tear created by these new blocks. The idea being that if the effort is reduced, the temperature at the contact point should decrease and the aggressiveness should be reduced.

To achieve a reduced braking effort the idea has been to have a simultaneous braking of all wagons, by an electric opening of a braking valve on each wagon. This would be an overlay on the actual braking system which will remain as a back up to guarantee the safety. The installation of an electric line all along the train would allow many other improvements and in particular the capacity to introduce the predictive maintenance among others as shown in the attached document elaborated by Knorr Bremse:

Figure 6: Advantages of EP brakes. – Source: Knorr Bremse

Knorr Bremse was in charge to analyze the impact of synchronous braking on the shoes temperature at the surface of contact with the wheel. At the same time KB performed an analysis to detect which element of this virtuous circle generated by the continuous electric line and the bus of information it was able to carry would have the highest impact on the operation efficiency.

KB was also in charge of modeling the braking of the new designed multi axel wagons in order to allow KTH to perform the analysis of the longitudinal efforts and give a preliminary opinion on the safety of these new designed wagons incorporated in different type of trains.

The results of KB work are described in the following tables:

Brake system design and simulation

1. Modelling of base variants
2. Sensitivity analyses
3. Base simulations of brake pipe behaviour for different train lengths, wagon lengths, brake types (conv. pneumatic UIC brake, EOT, MOT, EP) and scenarios (Full Service brake, Releasing, Emergency Brake)
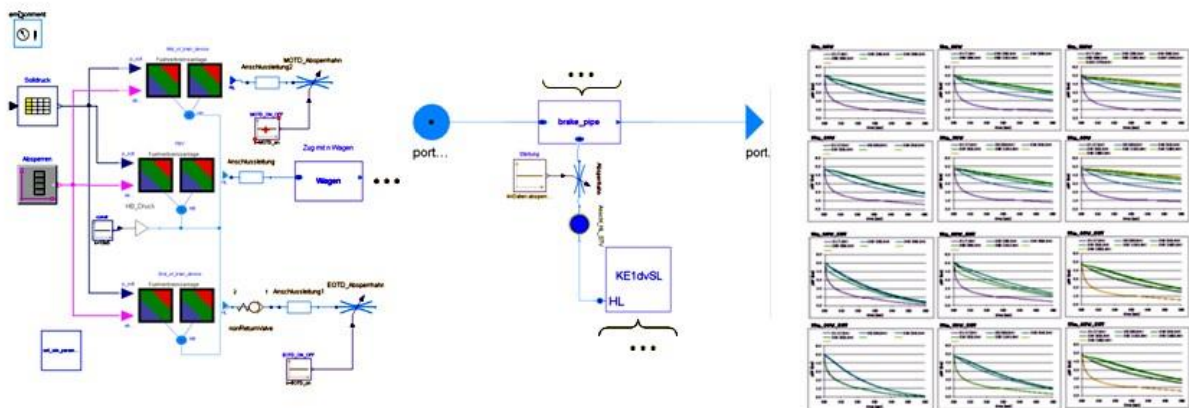
Figure 7: Brake system design and simulation. - Source: Knorr Bremse

Brake system design and simulation, cont'd

Individual brake system layouts and parameters for conventional and novel freight wagons Individual brake simulations based on interpolations between relevant base simulations and wagon-specific post-processing to generate the relevant pressure and force data for the respective brake equipment, loading state, brake mode etc.
Documentation of main results

The analysis performed are similar to what is displayed in the next table:

Exemplary Simulation Results – articulated 12 axle container wagon consist
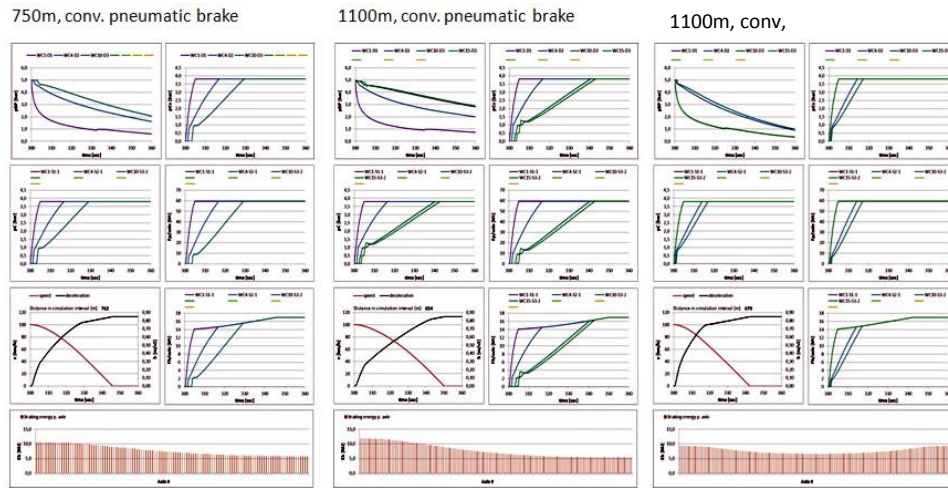
Figure 8: Exemplary simulation results. - Source: Source: Knorr Bremse

As regards the Braking performance to ensure a correct and safe stopping distance:

Braking performance of Ep brakes Given a 750m train of λ = 90% (all λ = 100%), Ep brake allows a reduction of train wagon

train braking distance from ≤ 900m to 700m (blue line in diagram)
Alternatively, given that its effect is fully rated in the braking weight, it allows to achieve 900m braking distance for wagons with 100/74 = 135% of their conventionally allowed axle load (green line in diagram)
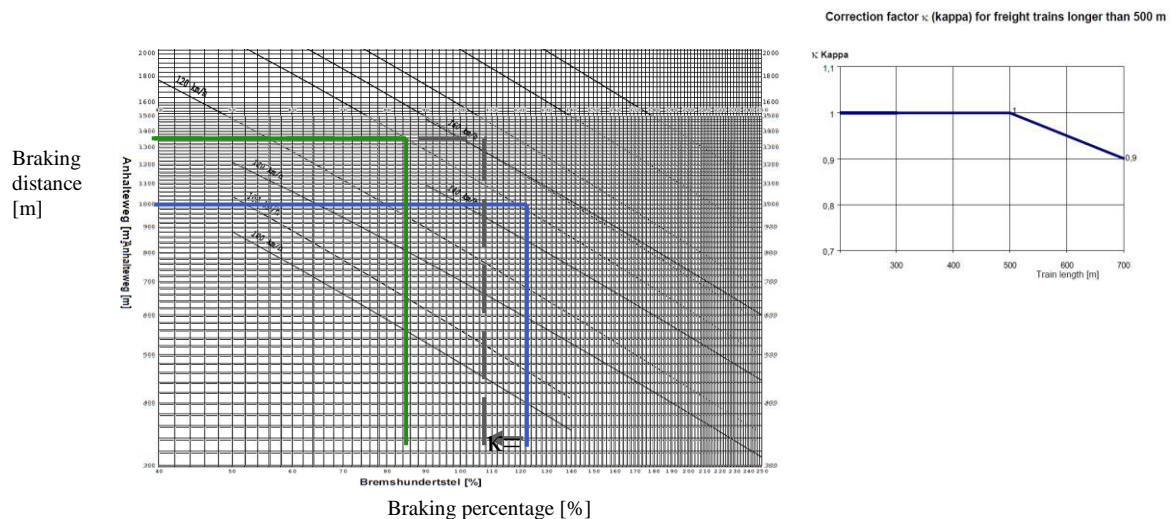
Figure 9: Braking performance of EP brakes. - Source: Source: Knorr Bremse

To appreciate the impact of certain methodology of braking on the temperature of the contact surface the methodology was to appreciate the energy involved in the operation and its distribution on the different axels of the train, an example of the simulation results is given here under:
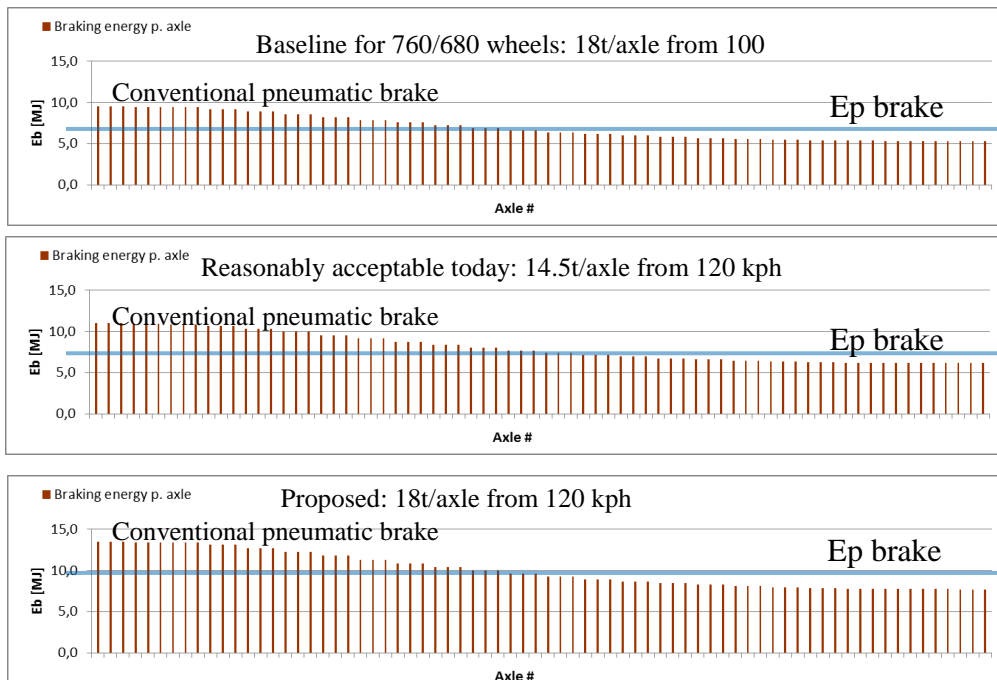
Figure 10: Braking energies. Emergency brakings with novel STVA 750m car transport train. – Source: KB
Braking Energies – Emergency braking's with novel STVA car transport train of 750m

The complete set of results of the simulations performed by KB are in a separate document which has been used by KTH to perform the analysis of longitudinal efforts and to assess the safety of the solutions.

3 Dynamic analysis for the various solutions to assess the stability and analysis of shoes and wheels wear and tear evolution by KTH

This part is to check the stability of the different new designs in the various conditions of operations. It is also to validate if there is a positive impact of various braking solutions on the shoes wear and tear and on the wheel wear and tear.

3.1 Dynamic analysis of novel vehicle concepts for improved network capacity

This chapter intends to verify the feasibility of the proposed vehicles from the dynamic point of view. The main innovations that have impact in the dynamics of the system are:

- Vehicle type and characteristics
- Brake type

3.1.1 Vehicle characteristics

From the wagon types under investigation in C4R, there are two types of vehicles whose dynamic analysis has been performed.

> Bogie wagons:
> Conventional 4-axle container wagons (type Sgg…), 840/760 wheels, 20t/axle
> Conventional articulated 6-axle container wagons (type Sgg…), 840/760 wheels, 20t/axle
> Novel articulated 12-axle container wagon consists, 840/760 wheels, 20t/axle
> Single wheel set wagons
> Conventional 2-axle short-coupled car transport wagons (type Laes), 760/680 wheels, 18t/axle
> Conventional 3-axle car transport wagons (type Laes), 760/680 wheels, 18t/axle
> Novel 6-axle car transport wagon consists (STVA concept), 760/680 wheels, 18t/axle

Modelling of these wagons has been performed according to the technical data provided by STVA and NTnet AB. The selected MBS software is Gensys[1]. When building the multibody simulation models, the local coordinate systems of the shared bogies and/or wheel sets has been referenced to the preceding car body.

The feasibility of these novel vehicles has been assessed by studying the dynamics of the different vehicles is split in two different cases: lateral dynamics (critical speed and curving behavior) and longitudinal dynamics (force transfer on buffers while braking).

3.1.2 Dynamic analysis: lateral dynamics

Simulation cases: critical speed

The simulation cases for the critical speed of the shared **bogie vehicles** have been summarized in table 1

	1 car	2 car	5 car
18 tons	340mm	340mm	340mm
	380mm	380mm	380mm
20 tons	380mm	380mm	380mm
	420mm	420mm	420mm
22.5 tons	420mm	420mm	420mm
	460mm	460mm	460mm
Empty car(s)	340mm	340mm	340mm
	380mm	380mm	380mm
	420mm	420mm	420mm
	460mm	460mm	460mm
Adjusted load 18 tons	340mm		
	380mm		
Adjusted load 20 tons	380mm		
	420mm		
Adjusted load 22.5 tons	420mm		
	460mm		

Table 1: Summary of simulation cases for critical speed calculations of articulated bogie vehicles. – Source KTH

In the given case table:

       The green column correspond to different axle load

       The red row correspond to varying number of cars

       The purple columns represent the different wheel radius for a particular load case and the number of cars.

Hence, in total there are 30 cases to be simulated.

In addition to the above 30 cases, there are an additional 6 cases, for single car bogie vehicle with axle load equal to the axle load at the end bogies of a 5 car articulated vehicle (reduced load). These cases

were performed in order to see the influence of the lower load in the first bogie for the articulated vehicles. Hence the total number of cases: 36.

Similarly, the simulation cases for the critical speed of the shared wheel set vehicles have been summarized in table 2

	1 car	2 car	5 car
18 tons	380mm	380mm	380mm
20 tons	420mm	420mm	420mm
22.5 tons	460mm	460mm	460mm
Empty car(s)	380mm	380mm	380mm

Table 2: Summary of simulation cases for critical speed calculations of articulated single wheel set vehicles – Source: KTH

In the empty case, the cars with the minimum wheel radius are only simulated since for larger radius,the critical speed will be higher.

The total number of simulation cases for the shared wheel set system is 12.

Simulation cases: curving behavior

The simulation cases for examining the curving behavior of the vehicle were decided on the basis of UIC 518 on testing and approval of railway vehicles from the point of view of their dynamic behavior-safety-track fatigue-running behavior.

Based on the guidelines, the vehicle is to be a tested for curve radius= 250m (small radius curve) and 500m (medium radius curve). The vehicle is to be tested at constant speeds corresponding to:

The equilibrium speed with a cant of 130mm.
Cant deficiency of 25% for the same speedin the first case. Cant excess of 10% for the same speed in the first case.

The list of the cases have been summarized in the table below with corresponding wheel radius(mm), load(tons),number of cars and the corresponding cant(mm):

Case	5car	1car
bogie-340-18t	cant 130	cant 130
	cant 143	cant 143
	cant 97,5	cant 97,5
bogie-380-18t	cant 130	cant 130
	cant 143	cant 143
	cant 97,5	cant 97,5
bogie-380-20t	cant 130	cant 130

	cant 143	cant 143
	cant 97,5	cant 97,5
	cant 130	cant 130
bogie-420-20t	cant 143	cant 143
	cant 97,5	cant 97,5
bogie-420-22,5t	cant 130	cant 130
	cant 143	cant 143
	cant 97,5	cant 97,5
bogie-460-22,5t	cant 130	cant 130
	cant 143	cant 143
	cant 97,5	cant 97,5
bogie-340-empty	cant 130	cant 130
	cant 143	cant 143
	cant 97,5	cant 97,5
bogie-380-empty	cant 130	cant 130
	cant 143	cant 143
	cant 97,5	cant 97,5
bogie-420-empty	cant 130	cant 130
	cant 143	cant 143
	cant 97,5	cant 97,5
bogie-460-empty	cant 130	cant 130
	cant 143	cant 143
	cant 97,5	cant 97,5

Table 3: Summary of simulation cases for curving behavior calculations of articulated bogie vehicles. – Source:KTH

The total number of cases to be simulated for determining curving behavior in case of the shared-bogie system is 60.

Similarly, for the **shared-wheel set** system:

Case	5car	1car
wheelset-380-18t	cant 130	cant 130
	cant 143	cant 143
	cant 97,5	cant 97,5
wheelset-420-20t	cant 130	cant 130
	cant 143	cant 143
	cant 97,5	cant 97,5
wheelset-460-22,5t	cant 130	cant 130
	cant 143	cant 143
	cant 97,5	cant 97,5
wheelset-380-empty	cant 130	cant 130
	cant 143	cant 143
	cant 97,5	cant 97,5
wheelset-420-empty	cant 130	cant 130
	cant 143	cant 143
	cant 97,5	cant 97,5
wheelset-460-empty	cant 130	cant 130
	cant 143	cant 143
	cant 97,5	cant 97,5

Table 4: Summary of simulation cases for curving behavior calculations of articulated single wheel set vehicles. – Source: KTH

The total number of cases to be simulated for determining curving behavior in case of the shared-bogie system is 24.

The cases described above correspond to simulations performed for a single value of curve radius.

Design of Boundary conditions: The boundary conditions for:

Critical Speed Simulation	The vehicle is initially given a high speed with a small value of retardation over the time interval of the simulation. Thus, the vehicle is initially unstable and reduces its critical speed until it becomes stable. The lateral displacements of the wheel sets are plotted as a function of speed to find the critical speed.

Curving Behavior	The vehicle is given the equilibrium speed for at a cant of 130mm in all the cases and the Y/Q ratio examined to determine the curving behavior. The UIC standards are followed, which require Y/Q to be lower than 0.8.

It is to be noted that in case of the simulations involving shared wheel sets, the non-linear friction elements prevent the simulation from starting because of mathematical errors while executing. To solve this, special simulations have been run with a slightly modified suspension to create a stable running vehicle. Later, these conditions and position of the vehicle are replicated as the initial running condition with the original vehicle, allowing the correct simulations to be performed.

Results and Discussions:

Critical speed: The critical speed in (km/h) corresponding to the different cases, all of them with a friction valueof 0.35 at the wheel rail contact, are described below:

5 car shared bogie model:

	680.00	760.00	840.00	920.00	Wheel Diameter (mm)
18.00	83.00	87.00	X	X	
20.00	X	92.00	96.00	X	
22.50	X	X	102.00	106.00	
Axle load(tons)					

Table 5: Critical speed value for 12 axlearticulatedvehicle, laden. – Source: KTH

Wheel Diameter (mm):	Critical speed (km/h)
680.00	64.00
760.00	67.00
840.00	69.00
920.00	71.00

Table 6: Critical speed value for 12 axlearticulatedvehicle, empty. – Source: KTH

2 car shared bogie model:

	680.00	760.00	840.00	920.00	Wheel Diameter (mm):
18.00	81.00	85.00	X	X	

20.00	X	90.00	94.00	X
22.50	X	X	101.00	104.00
Axle load(tons)				

Table 7: Critical speed value for 6 axlearticulatedvehicle, laden. – Source: KTH

Wheel Diameter (mm):	Critical speed
680.00	64.00
760.00	67.00
840.00	68.00
920.00	72.00

Table 8: Critical speed value for 6 axlearticulatedvehicle, empty. – Source: KTH

Single car with 2 bogies:

	680.00	760.00	840.00	920.00	Wheel Diameter (mm):
18.00	95.00	100.00	X	X	
20.00	X	109.00	113.00	X	
22.50	X	X	121.00	123.00	
Axle load(tons)					

Table 9: Critical speed value for 4 axlesinglecarvehicle, laden. – Source:KTH

Wheel Diameter (mm):	Critical speed
680.00	61.00
760.00	63.00
840.00	66.00
920.00	68.00

Table 10: Critical speed value for 4 axlesinglecarvehicle, empty. – Source: KTH

Single car with 2 bogies (with adjusted load):

	680.00	760.00	840.00	920.00	Wheel Diameter (mm):
18.00 ton equivalent 20.00 ton equivalent 22.50 ton equivalent	78.00	81.00	X	X	
	X	86.00	89.00	X	
	X	X	98.00	101.00	
Axle load(tons)					

Table 11: Critical speed value for 4 axlesinglecarvehiclewithreducedverticalload, laden. Source: KTH

5 car shared wheel set model (loaded):

	760.00	840.00	920.00	Wheel Diameter (mm):
18.00	148.00	X	X	
20.00	X	210.00	X	
22.50	X	X	197.00	
Axle load(tons)				

Table 12: Critical speed value for 6 axlearticulatedcar transport vehicle, laden. – Source: KTH

2 car shared wheel set model (loaded):

	760.00	840.00	920.00	Wheel Diameter (mm):
18.00	190.00	X	X	
20.00	X	226.00	X	
22.50	X	X	252.00	
Axle load(tons)				

Table 13: Critical speed value for 3 axlearticulatedcar transport vehicle, laden. – Source: KTH

Single car with 2 wheel sets(loaded):

	760.00	840.00	920.00	Wheel Diameter (mm):
18.00	330.00	X	X	
20.00	X	440.00	X	
22.50	X	X	485.00	
Axle load(tons)				

Table 14: Critical speed value for 2 axle short-coupledcar transport vehicle, laden. – Source: KTH

Empty wagons with wheel diameter 760mm

Case	Critical speed (km/h)
5 car shared wheel set system (empty)	111.00
2 car shared wheel set system (empty)	165.00
1 car shared wheel set system (empty)	110.00

Table 15: Critical speed value for the different car transport vehicleconfigurations, empty. – Source: KTH

Conclusions: bogie vehicles
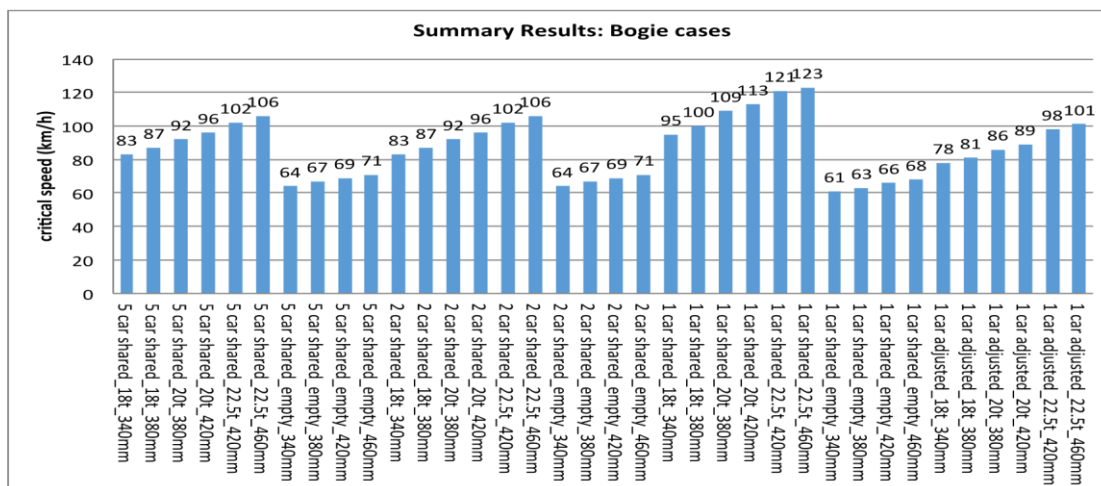
Figure 11: Summary of the critical speed of the shared bogie cases. – Source: KTH

The theoretically calculated critical speeds for bogie vehicles are relatively low compared with the speeds these vehicles are designed to run in real life, i.e. 100km/h laden and 120km/h empty. This has been investigated but no satisfactory answer has been found. In fact, theoretical studies of empty Y25

wagons in the literature [2], [3]deal with critical speeds between 60km/h and 80km/h, similar to the ones obtained in this study. It should be mentioned that the friction value in the contact patch is 0.35. If this value is reduced to 0.15, the critical speed increases substantially, up to more than 100km/h. The study is still kept with the original friction value because the relative comparison between the reference vehicle and the novel vehicle is still valid.

For a better understanding of the figure, a reduced case set is depicted in the next figure. The critical speed for the 1 car vehicle is used as reference, a regular container transport with Y25 bogies. When using an articulated configuration, critical speed is reduced ca. 17%, but it is not important the number of wagons coupled in the configuration. This is because the ultimate cause for the reduction of critical speed is not about the number of vehicles, but about the axle load. In the articulated vehicles, first and last bogies have a reduced axle load compared to the intermediate wheel sets, so the critical speed is slightly reduced. In order to study the effect of load reduction on the single non-articulated vehicle, another case has been simulated with a single vehicle with a load equivalent to the first wheel sets in the articulated configurations. In this case the speed is reduced even below the articulated configurations.
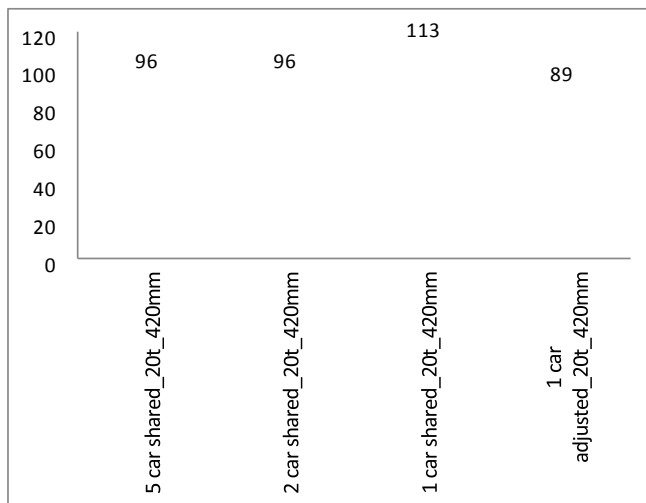
Figure 12: Summary of the critical speed of the shared bogie cases. - Source: KTH

The main conclusion is that the fact that vehicles are articulated positively affects the critical speed, while the mandatory reduction of the load in the first wheel sets affects negatively the speed when the vehicle gets unstable. The total expected reduction in the top speed is lower than 20% for laden vehicles and no reduction for empty vehicles, using the existing non-articulated Y25 vehicles as a maximum speed reference.

Conclusions: single wheel set vehicles
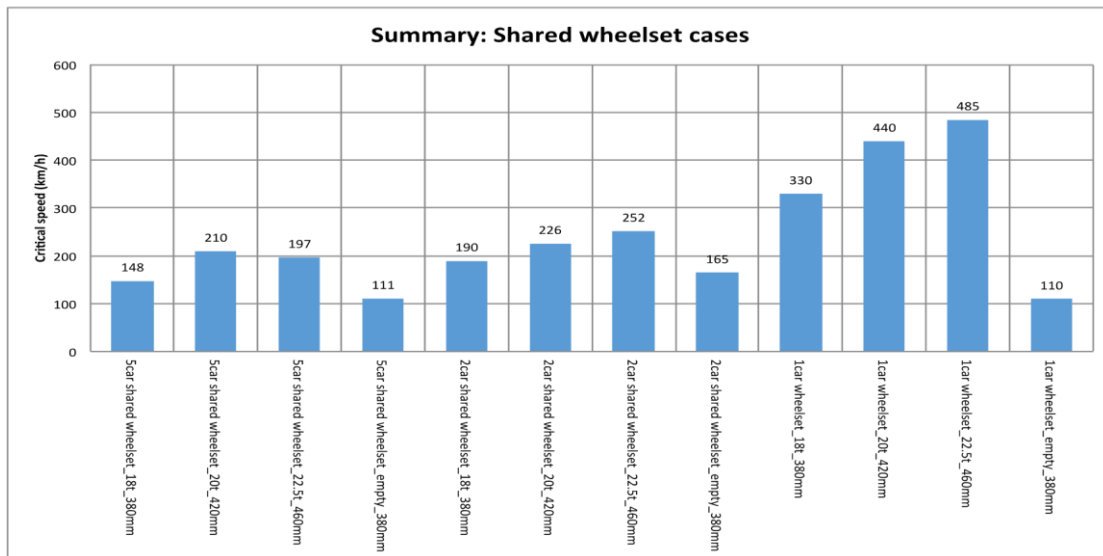
Figure 13: Summary of the critical speed of the shared wheel set cases. - Source: KTH

Single wheel set consists, in any configuration and any load case, have no theoretical issues with the critical speed of the vehicle. For a conservative friction value of 0.35, the most limiting speed is for 5 car articulated empty vehicles, which is the same as for the shortcoupled reference, meaning that there is no theoretical decrease in the critical speed when using several vehicles coupled in a single consist. For the laden case, critical speed increases with axle load and wheel diameter, and is higher than 148 km/h for any case. The critical speed is not the limiting factor for single wheel set configurations.

Curving Ability:
The curving simulation of the single car was first performed for the case of a small radius of 250m for a single car. But, due to the particularities of the articulated model, simulations with a radius of 250m could not be carried out. Due to the limitations in calendar time, simulations have subsequently been performed for a radius of 500m only. This does not mean that the 5 car models cannot run in real life in low radius curves, it is just the mathematical model that could not converge for the applied conditions.

The designed track is of 2 kms with track irregularities in it. The transition curve is 120m long over the course of which the radius decreases and the cant increases linearly.
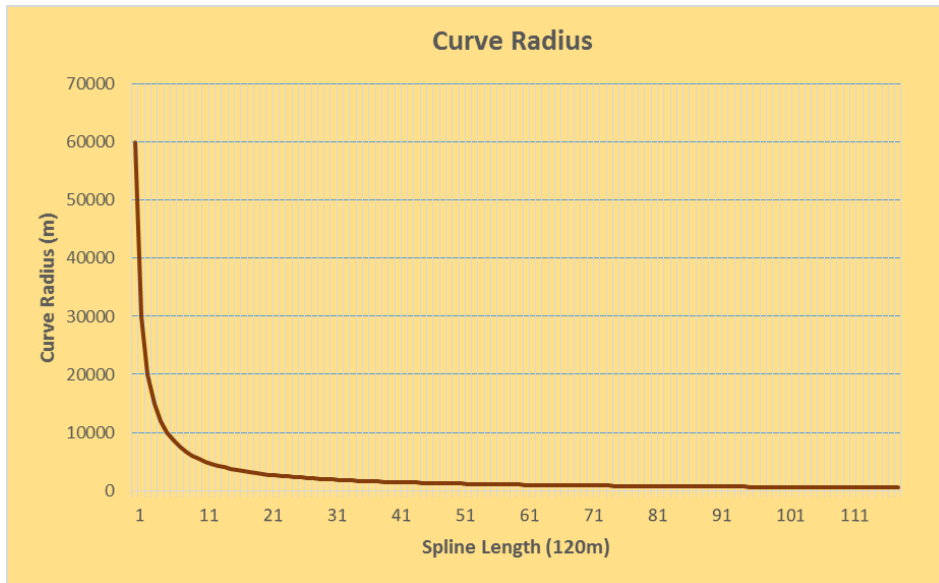
Figure 14: Curveradiuscharacteristics. - Source: KTH
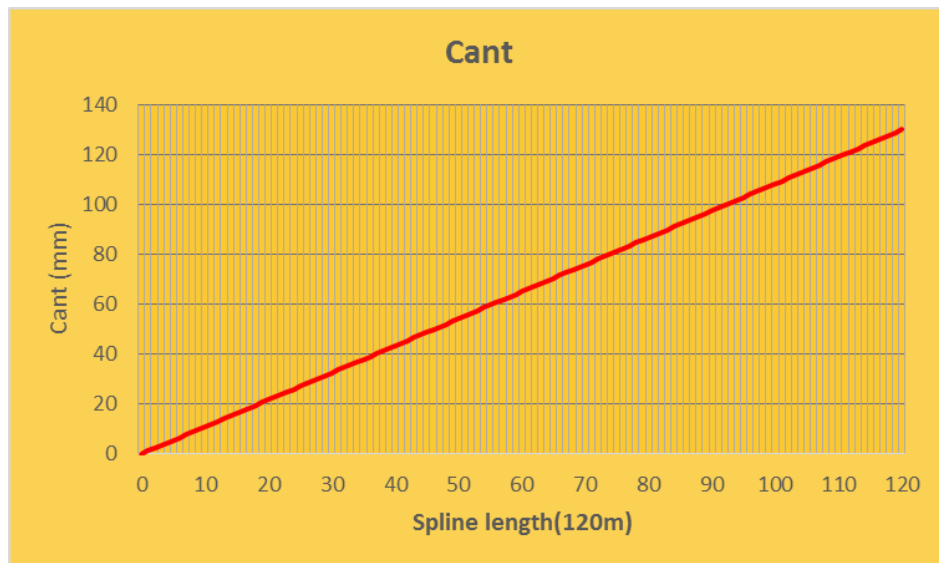
Figure 15: Curveradiuscharacteristics. - Source: KTH

For the given curve radius (500m) and cant (130 mm), the equilibrium speed is calculated as 75.86 km/h. This speed was used in the he equilibrium condition, cant excess and cant deficiency conditions by modifying the cant in the last two conditions.

The curving simulations yielded a value of **Y/Q lower than 0.8** in all the cases hence proving it stable during curving.

An histogram for one of the cases is described in the figure 16:

Figure 16 Type of Histogram
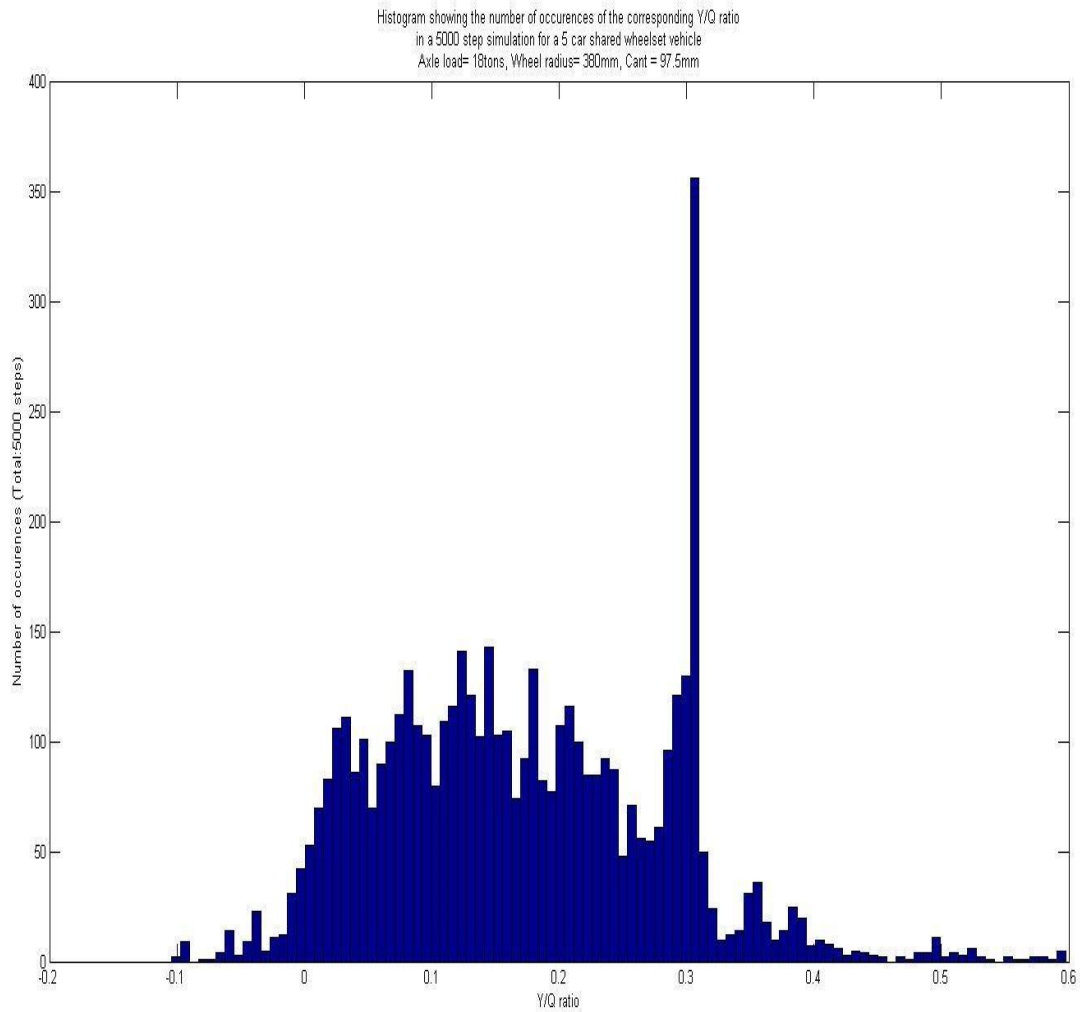
Figure 16: Type of histogram. - Source: KTH

3.1.3 Dynamic analysis: longitudinal dynamics

Longitudinal dynamics refers to the longitudinal forces transferred through the buffers of inter-wagon couplings.

The idea in this task is to assume that brake application is ideal, so the timing for the different braking solutions is a known variable. Then, with a one dimensional model of the train we can calculate the longitudinal force transfer between different wagons. Also, the influence of buffer distance for low radius curves.

3.1.3.1 Vehicle configurations

In order to study the influence of braking technologies on longitudinal force transfer, different vehicles are considered: VEL-wagon, articulated bogie vehicles and articulated single axle vehicles. Full trains with the different wagons will have different number of wagons and axles, and a different distance between couplers, which will enable a comparison between different business needs.

VEL-wagon: VEL wagons are a novel concept based on the EU project "Versatile, Efficient and Longer Wagon for European Transportation" (December 2010 to December 2012). It is highly modular and can accommodate ISO containers up to a length of 80'.
Shared bogie container transport vehicles Single axle car transport vehicles

3.1.3.2 Brake control modes

The main objective of this task is to allow a fair comparison between different braking control technologies in order to decide if the technical advantages of using novel and/or more expensive brake control systems is cost efficient. The technologies to be investigated are classic pneumatic (P) control, pneumatic control with End of Train device (EoT) and electro-pneumatic (EP) braking.

P brakes
In this first case the braking signal is transferred via the pneumatic circuit. When the brake valve is released, compressed air from the signal pipe is evacuated, and when the pipe is empty at the position of the wheel set, the brake actuation starts. This means that the signal travels through the pipe at the speed that of the air evacuating the pipe, so the brakes will start functioning in a progressive pattern. There is not one single configuration for the pneumatic braking. There are UIC provisions, but also national provisions which may deviate from the initial ones. UIC 421 provisions are as follows:

P (= loco and all wagons in P) up to a hauled mass of 800t

G/P (= loco in G, all wagons in P) between 800t and 1.200t

LL (="Long Locomotive", i.e. loco plus first five wagons in G, remaining wagons in P) between 1.200t and und 1.600t.

G (=loco and all wagons in G) between 1.600 t and 2.500t (= maximum admissible hauled mass), vmax = 100 kph

Other configurations are possible if a safety assessment is carried out. This applies, for instance, to centre buffer couplers [UIC 421] German DB Ril 402 provisions are as follows:

P up to a hauled mass of 1.600t; 2.500t if all wagons > 32t and up 4.000t if all wagons > 40t
P is generally allowed if stabilizedcenter-buffer couplers according to UIC are used.

Due to the different pneumatic brake configurations that can be found in the trains, in the following work P will be studied, where all the brake cylinders have the same force characteristic. Timing data for the simulations will come from Knorr-Bremse's simulations.

P brakes with EoT device
When looking for cost efficient solutions for novel braking systems, one of the most promising ones is the use of an End of Train device, a radio operated valve that releases the air from the end of the pipe when the brake is applied. Thus, the end of the train and the front start braking at the same time, and the delay caused by the speed of the air evacuating the pipe is then mitigated. Also, the total delay until all brakes are activated is halved.

In this case, the timing data will also come directly from Knorr-Bremse's simulations.

EP brakes
In this case, the braking signal is provided by an electronic system, ensuring that all wheel sets get the braking signal almost simultaneously. The downside is that the wagons would need couplers that

include electric connections, which makes it a costly solution. This cost is reduced in cases where long wagons are used and connected by drawbars.

From a practical point of view, it is considered that all the brakes act at the same time. In this case, there is no transfer of longitudinal force between cars, as all cars have the same force at the same time. Thus, this case will not be simulated.

3.1.3.3 Technical data

Individual brake application

Each brake cylinder has a load curve, as it is not instantly applying the maximum force. This is dependent on the braking mode of the wagon.

> Load curve (F(t)) for the block brakes: (limits are acc. to UIC 540, TSI WAG also refers to this)
> Slow G-Mode: If released brake is getting applied:
> Quick built-up of ca. 10% of the max. brake cylinder force within few seconds ("inshot function").
> Slower remaining force build-up within 18-30 sec until 95% of max. force.
> Normal P-Mode: steady built-up time, at emergency brakings within 3-5 sec (6 sec if load braking) between start and 95% of max. force reached – KE distributor valves xx sec
> Releasing Load curve (F(t)) for the block brakes:
> Slow G-Mode: within 45-60 sec from start to falling below 0.4 bar cylinder pressure Normal P-Mode: within 15-20 sec from start to falling below 0.4 bar cylinder pressure, within 15-25 sec for freight cars > 70t

The real values of brake application and releasing times scatter quite widely within the above limits. Even for the Knorr KE distributor valve there are different variants, and above all, the times are temperature dependent. As a conservative assumption, KB suggests to use 21s application time in G mode and 3.5s in P mode. These values correspond to the lower limits of the somewhat narrower EN 15355.
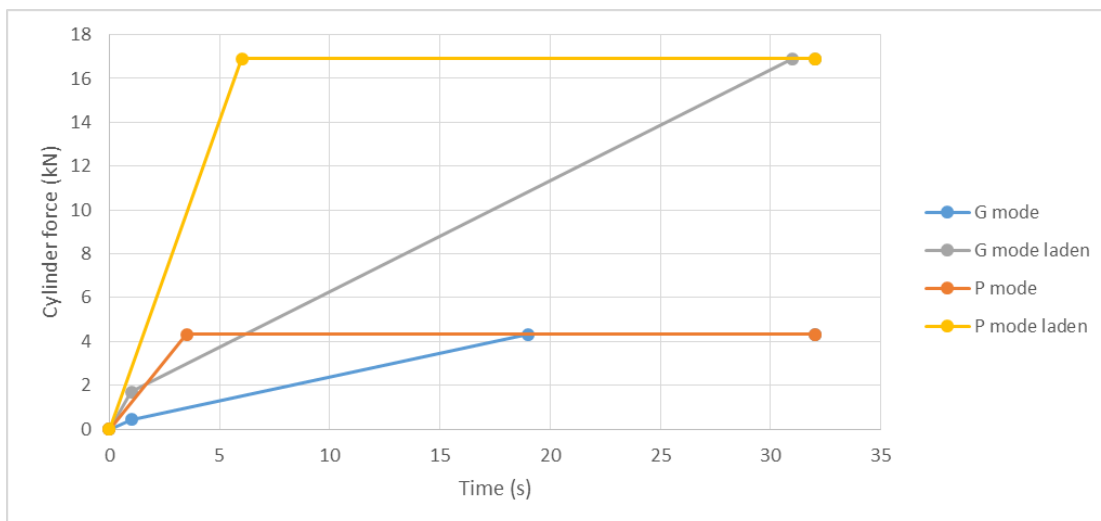
Figure 17: Loading characteristics according to the data provided by KB. – Source: Knorr Bremse

3.1.3.4 Modelling and simulation

The calculation is performed with one-dimensional models in Gensys. The model includes all the vehicles in the consists with their individual characteristics, the force-displacement and force-speed characteristics of the connections between car bodies, and the force and timing of the brake applications in each vehicle according to the simulations from Knorr Bremse.
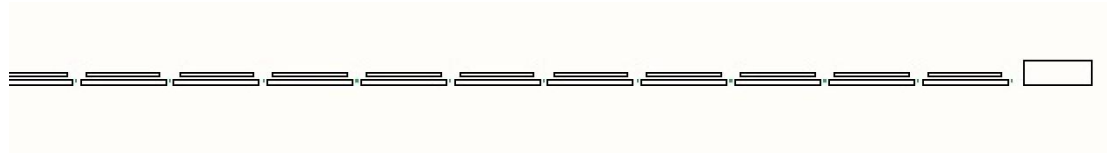
Figure 18: Example of a model with a locomotive and several wagons. – Source: KTH

3.1.3.5 Results and discussion

The results on this topic are still preliminary, so they are not included in this report.

3.2 Perspective on wheel damage due to block brakes

Block braking dissipates kinetic energy in the form of heat, which is partly transferred to the wheels and dissipated by them. This has major maintenance problems as temperatures above 500°C maintained for a certain period of time can cause different damage modes to appear, e.g. tread shelling.

The selected brake system, EP brake with brake blocks, has advantages regarding the time block brakes are acting on the wheels of the front part of the train, so the total heat transfer to these wheels will be reduced. Also, a reduced wheel diameter for an improved vertical gauge causes that the cumulated thermal energy is increased, so this innovation will probably decrease the life of the wheel sets.

Braking mechanics, thermal energy transfer and dissipation, thermal damage, and brake tribology are complex phenomena with complex interactions that need deep research in order to be fully comprehended. The time availability in C4R only allows for minor efforts towards the theoretical study of the benefits on maintenance when the braking control system is changed; this problem definitely needs further and deeper investigation in order to be able to obtain sound conclusions applicable in daily train design and operation.

The main objective of this section is to give an insight to the gains that could be achieved by using P-EoT or EP braking instead of P braking in tread-braked vehicles. The process is as follows

> Literature review: gather all the information there is about wheel damage related to thread braking. Separate it by topics:
> Temperature build-up in the wheels
> Damage in the wheels
> Material softening (reduced young modulus)
> Wear transitions
> Hot spots
> Crack development
> Relate the two previous points: damage as a function of temperature (and ultimately braking)
> Braking time calculation for the proposed configurations, and extrapolation of the results in the previous literature review to the C4R case.

3.2.1 Temperature development due to braking

According to [4] the brake temperatures have a specific trend as in this figure:
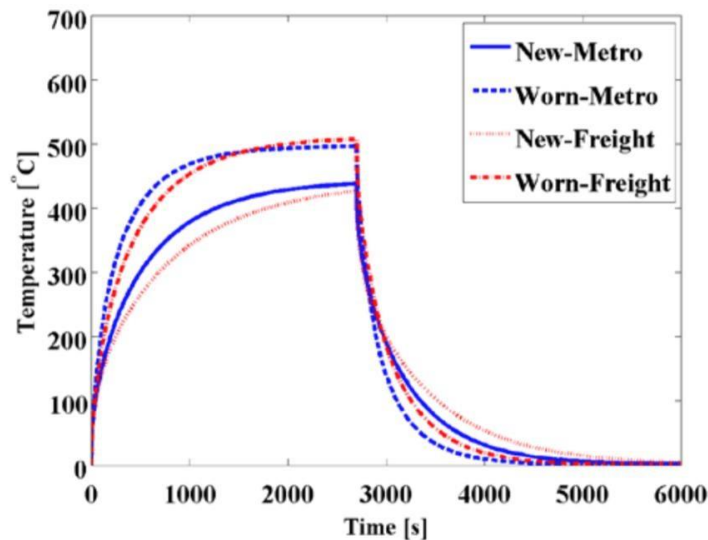
Figure 19: Calculated maximum temperature on the tread for drag braking with rail chill.[4] – Source: KTH

This means that the brake is sustained for a very long time, while maintaining the speed constant. If we stick to the first ca. 60s of this figure, that would be the temperature increase in a regular brake to stop, ca. 150°C.

3.2.2 Damage due to thermal effects

In [5] the crack increase due to thermal loading is analyzed.

"The results imply that fully functional brake systems are not likely to induce thermal crack propagation under normal stop braking, but that with pre-existing defects, a severe drag braking due to malfunctioning brakes may cause very deep cracking.These are "wheel braking cracks" which would completely destroy the wheel, so it is a safety issue and not a maintenance-related one.

In other paper [6] the relationship between the temperature and the wear regime transitions are studied. "Wear transitions occurring during running-in are decisive for the outcome of the rest of the test run."
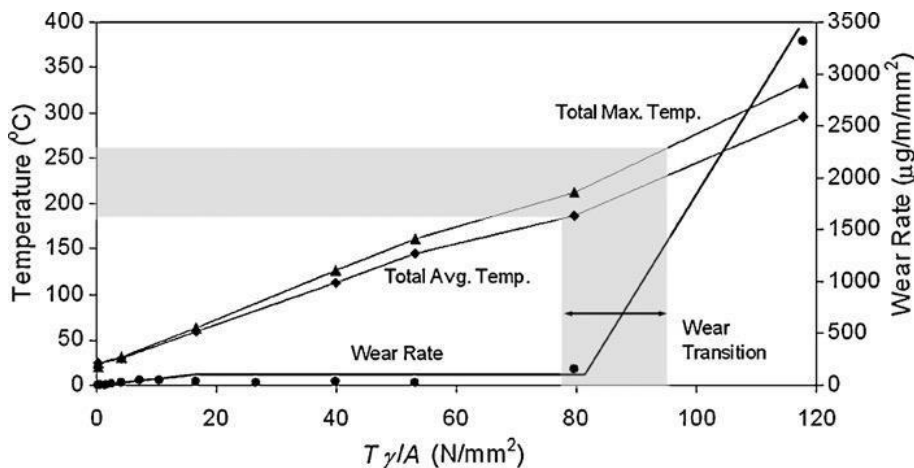
Figure 20: Wear transition dependence with temperature [6]. – Source: KTH

The figure shows that wear transition happens after ca. 200°C: "The British Steel Makers Creep Committee demonstrated that carbon manganese steels, similar to rail steels, experience thermal softening at approximately 200–300 °C, causing a drop in the yield strength." [*British Steel Makers Creep Committee, BSCC High Temperature Data, the Iron and Steel Institute for the BSCC, London, 1973*] Also, "Widiyarta et al. have modelled the thermal effects in ratcheting wear. It was found that the temperature rise at the contact surface will lead to an increased rate of damage accumulation by ratcheting causing a significantly increased wear rate and propensity for crack propagation." Anyway, temperature seems to have different effects:

> Thermal softening, which will increase wear rates.
>
> Microstructural surface changes
>
> To finer grain structures, which will decrease wear rates.
>
> To austenitic structures that generate catastrophic wear.

Another reference [7] studied wear of block materials, but not wheels, concluding that around 550°C for cast iron and 500°C for organic there is a wear transition. There is no apparent wear transition for sinter block brake materials. This is only blocks and not wheels. There should also be taken into account the differences in thermal conductivity for novel materials, which will reduce the heat conduction through them and thus increase wheel temperature.

For cast iron there is an increase and then decrease, due to the initial generation of an oxide layer which is brittle compared to the metal, and then is hardened again when the oxidation layer is increased enough to be resistant again.
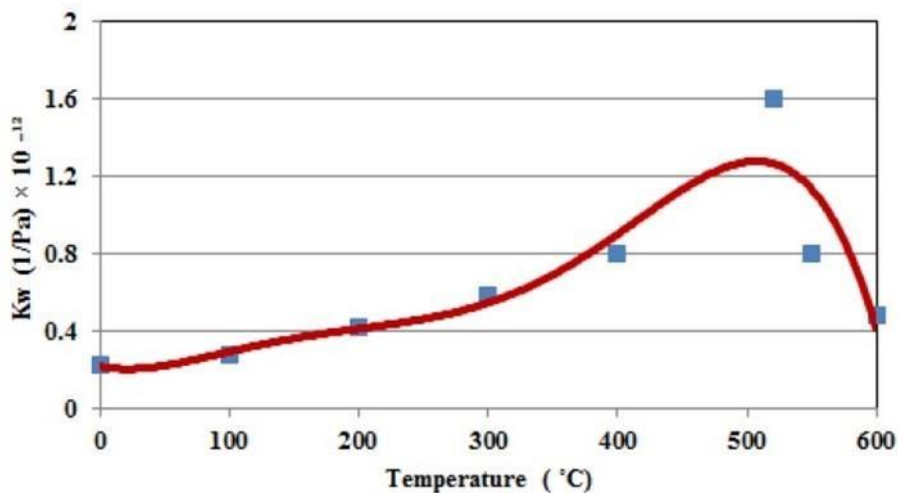
Figure 21: Wear coefficient dependence on temperature[8]. – Source: KTH

Here they study the influence of temp on ratcheting damage [9]. As it can be seen in the next figure, the normalized yield stress is minimal between 400°C and 500°C.
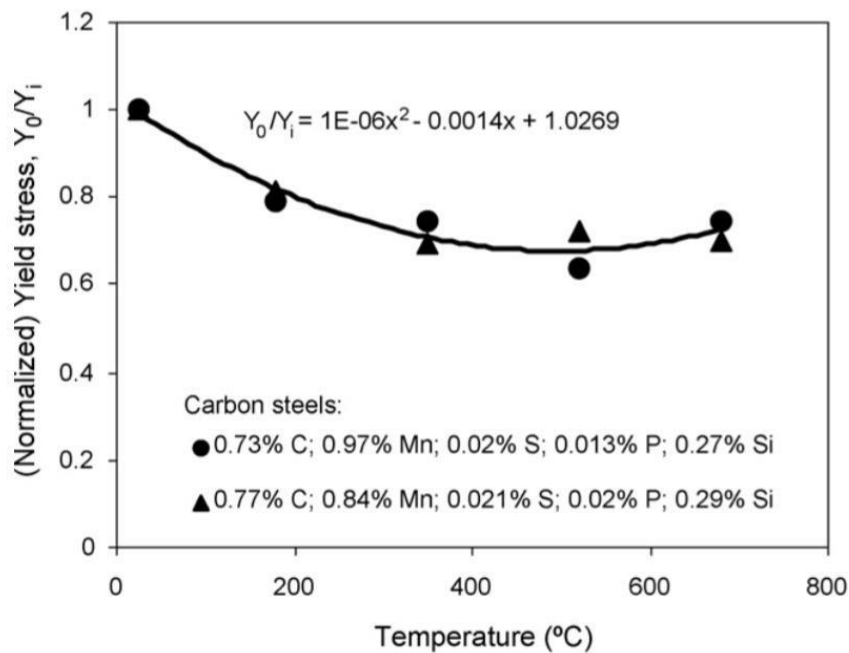
Figure 22: Yield stress dependence on temperature[9]. – Source: KTH

In this article, wheel-rail rolling generated contact is analyzed. There, it is stated that, for a single wheel pass and normal running conditions, the temperature in the wheel is not enough for phase transformation at min 600°C [10], but it is enough for a weakening of the material (yield stress reduction of up to 40%). With a slip-roll ratio of -5%, the subsurface temperature is plotted in the next figure.
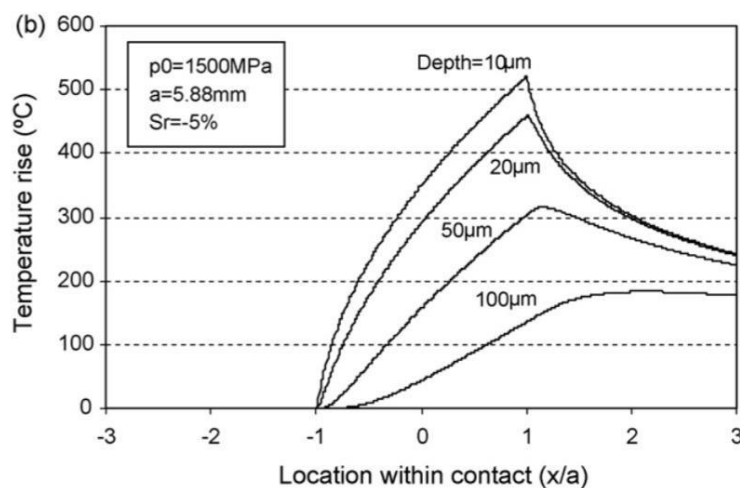
Figure 23: Sub-surface temperature rise in the wheel-rail contact[10]. – Source: KTH

Eventually, material softening favors ratcheting accumulation, speeding up material failure. There is also an increased wear rate and the material has a propensity for crack initiation.

3.3 Benefits of EP braking regarding thermal damage

After this review, the question remains if introducing EP brakes will reduce wheel damage.

The reasoning is depicted in Figure 24.

EP Brake → Reduced brake → Reduced energy → Reduced Temp. → Reduced Thermal

Figure 24: Damage reduction due to EP braking. – Source: KTH

Now, as the time for this calculations is rather limited, the work has been performed in the following way:

From KB calculations, the time delay between P braking and EP braking is obtained. Alternatively, the energy dissipated in each wheel can be obtained.

From these results and according to scientific literature, a temperature at the wheel tread is estimated.

With the estimated temperature, the thermal damage types that are most likely to occur on the wheel will be discussed, specially the possible reduction of the different types of damage.

The study is carried out for articulated 6-axle container consists with Y25 running gear, carrying K-blocks and load braking limit 16t/axle and the following conditions:

750m trains with conventional pneumatic brake

750m trains with EP brake

1100m trains with conventional pneumatic brake

1100m trains with radio End-of-Train device (EOT)

1100m trains with EP brake

The qualitative results are applicable to any vehicle that changes from P to EP brakes. Brake time

Configuration	t(s)
a) 750m trains with conventional pneumatic brake	46,4
b) 750m trains with EP brake	37,7
c) 1100m trains with conventional pneumatic brake	52,1
d) 1100m trains with radio End-of-Train device (EOT)	41,5
e) 1100m trains with EP brake	37,8

The biggest difference in brake time is ca. 15s between cases e) and c).

Brake temperature

As it has been seen before, the temperature increase in 60s is ca. 150°C. Assuming a linear increase, the temperature will be reduced from 130°C (c) to 100°C (e).

Wheel damage

As it has been seen in the literature review, thermal damage appears in the following thresholds:

Material softening: around 5% between 130°C and 100°C (as in the current worstcase scenario)

Wear ratio: 200-300°C to 500-550°C depending on the publication

Hot-spots: >500°C

Increased crack propagation: during regular rolling contact, ratcheting is favored due to thermal effects. Not studied for braking contact.

4 ELECTRIFICATION

4.1 Central Auxiliary Power Supply

Centralized power supply also known as Head-End Power is provided by one or more locomotives in the train. In some cases there are also dedicated GenSet cars providing power to the rest of the train. The central power supply system requires a cabled connection with appropriate connectors throughout the whole train. I.e. all cars of a train have to be equipped.

In the following, existing and service-proven railway standards are examined regarding their basic suitability to provide power and communication to a freight train.

The power supply to the train originally was originally used to charge chemical batteries used for lighting and ventilation purposes of passenger trains. The corresponding power demand was relatively low.

4.1.1 UIC 522

Later, vapor heating was replaced by electric heating and a train power supply system based on jumper cables and connectors according to UIC552 was introduced. The RIC cars must be able accept at all the following four voltages: 1,000 V AC 16 2∕3 Hz, 1,500 V AC 50 Hz, 1,500 V DC and 3,000 V DC. The connectors are rated with 600A – 800A[1]. The transferrable power is in the range of 600kW – 1800kW (dependent of the supply voltage, which is in turn dependent of the catenary voltage). The total power supplied is not only sufficient for heating purposes and battery charging but also to for passenger car air conditioning   purposes.

The power line is a single-pole connection. The return current is transferred via the rail.

The obvious advantages of this system are:

Service-proven system components.

15kW electric power for each of all typically 40 cars of a European 750m freight train. Most electric freight locomotives are equipped with the corresponding outlet.

Figure 25: Schaltbau ZH series UIC 522 connector. – Source: Schaltbau

On the other hand, the following disadvantages can be stated:

The UIC552 standard does not comprise any means for data or information transfer.

The cable cross section of 185mm² leads to heavy and costly equipment.

The applied voltages of 1000V - 3000V requires converters in each car to supply a regulated low voltage (e.g. 24V DC, 110V DC or 400V 3~AC) usable for the targeted consumers.

The anticipated power demand of electric/electronic consumers on freight cars is one or two orders of magnitude smaller than the possible supply of 15kW. The whole system is oversized and consequently too costly.

4.1.2 UIC 558

The UIC 558 standard describes an alternative, well-established system to transfer electric signals (and associated a small amount of power) within the train.

UIC 558 desribes an 18-pole cable and connector with partly standardized assignments.

Pair of Wires		Function	Signal	Group
1	2	Audio towards train loudspeaker	2 Veff (100-8000 Hz)	1
3	4	Voice communication towards:	1.6 Veff (100-5000 Hz)	1
3 (-)	4 (+)	- the driver	18-33 Vdc (permanent)	
3 (+)	4 (-)	- the switchboard	18-33 Vdc (permanent)	
5 (+)	6 (-)	Switch on loudspeaker amplifiers	18-33 Vdc (permanent)	2
7 (+) 7 (X*)	8 (-) 7 (Y*)	Priority of announcement command TCN* Communication	18-33 Vdc (permanent) 6-9 Vpp (500 kpbs)	2

₁ 800A at lowtemperatures (-10°C)

9 (+)	12 (-)	Remote command of door closing	15-33 Vdc (pulse < 2 sec)	3
10 (+)	12 (-)	Remote command: light on	15-33 Vdc (pulse < 2 sec)	3
11 (+)	12 (-)	Remote command: light off	15-33 Vdc (pulse < 2 sec)	3
14 (+)	12 (-)	Unlock right doors command	15-33 Vdc (pulse < 2 sec)	4
15 (+)	12 (-)	Unlock left doors command	15-33 Vdc (pulse < 2 sec)	4
16 (+)	12 (-)	Remote control of door locked condition	Vdc level (permanent)	
17 (X)	18 (Y)	TCN Communication	6-9 Vpp (1 Mbps)	
S		Shield of wires 17-18		
13		Common shield for all wires		

Table 16: Signal description on 18pole cable. – Source: Knorr Bremse

Among a multitude of operator-specific signal assignments there also exists an ep-Brake control pulse implemented on wires 10-/12+ for braking 11-/12+ for venting.

If one would use this cable/connector system for alternative freight purposes, voice communication as well as light- and door commands are not required. Hence the corresponding wires could be used for different purposes. Even the standardized TCN communication with the low bandwidth of 1Mbps should not be targeted for future applications.

Figure 26: UIC 558 connector system©era-contact GmbH. – Source: Knorr Bremse

In order to provide power and data communication, one could think about using the existing system of connectors and jumper cables but with different wire assignments.

(One or) two pairs could be used for train-wide networking (e.g. TCN, CAN, Ethernet …) The remaining 7(or 8) pairs could be used for electric power transfer.

Assuming that seven pairs are available for DC electric power, the voltage drop caused by the total cable length imposes severe limitations for the power transmission capability: To explore the system limits, the following boundary conditions and assumptions are provided:

> Each contact pin and each wire (1mm²) is rated for a continuous current of 10A. Each car represents a total resistance of 0.8 Ohm for supply- and return line (one pair of wires). Assumption: Car harness having a total length of 2 * 22m = 44m using 1mm² copper wires.
> Dependent of the selected supply voltage, EN 50155 specifies a minimum permanent voltage of 0.7 * U_{nom} U_{nom} =   24V U_{min} = 16.8V
> U_{nom} =   48V U_{min} = 33.3V
> U_{nom} = 110V U_{min} = 77.0V

As a dedicated new system is to be designed, the EN50155 voltage specifications should be extended to U_{min} = 0.5 U_{nom}, in order to maximize the transferrable amount of power. The implications will be shown for 48V DC and 110V DC.
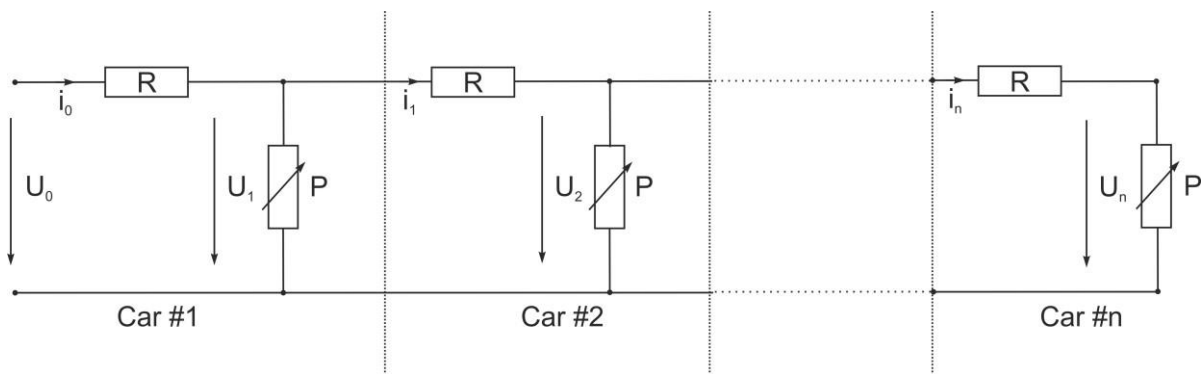
Figure 27: Electrical schematic assuming equal power consumers for all cars. – Source: Knorr Bremse

As only very limited amounts of power can be transmitted, it seems adequate to take special care to the equilibration of power among the cars. Therefore it is assumed that all electronic systems limit the power drawn per car independently of the actual voltage.

4.1.2.1 U_{nom} = 48V
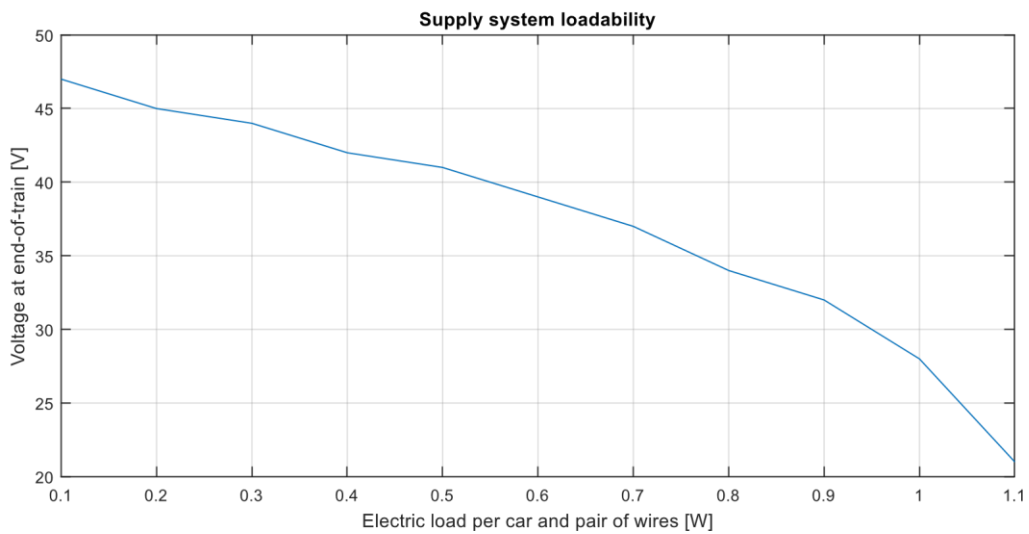
Figure 28: Loadablity at 48V. – Source: Knorr Bremse

Figure 28 shows the voltage at the trailing car at the train's end as a function of equal and constant power drawn by each car. For loads larger than 1.1W there is no stable power transmission possible. Hence the transferrable power has to be limited to 1W for one pair of wires resulting in a total power of 7W per car for all seven available pairs of wire.

4.1.2.2 U_{nom}= 110V
Figure 29 depicts the same situation for a 110V feeding of the power supply line.
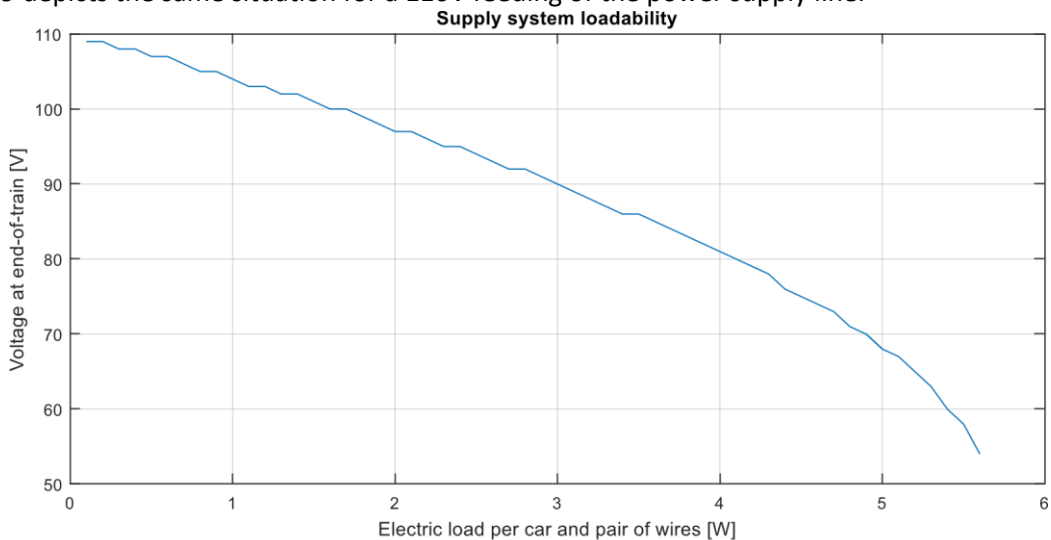
Figure 29: Loadability at 110V. – Source:Knorr Bremse

The total transferrable power on seven pairs is rising to 35W per car.
Figure 29 shows the voltage at the trailing car at the train's end as a function of equal and constant power drawn by each car. For loads larger than 5.5W there is no stable power transmission possible.

Hence the transferrable power has to be limited to 5W for one pair of wires resulting in a total power of 35W per car for all seven available pairs of wire.

For electronics comprising one or two ECU's, Sensors, wired and wireless Communication a power rating of 35W seems to be sufficient.

4.1.3 AAR ECP

The cable-based ECP Specifications consist of the following documents:

S-4200 –"Performance Requirement for ECP Cable-Based Freight Brake Systems" S-4210 – "Performance Specifications for ECP Brake System Cable, Connectors &Junction Boxes"

S-4220 – "Performance Specification for ECP Brake DC (Head End) Power Supply" S-4230 – "Intra-Train Communication Specification"

The inter car connection cable is a two-pole hermaphroditic cable specified for 230V DC operation and utilizes a #8awg cable which is approximately equivalent to a metric crosssection of 10mm².

The locomotive-mounted trainline power supply (TPS) has a rated output power of approximately 2500W. The TPS is fully capable of load sharing with othertrainline power supplies.

Figure 30: Inter-car-cable with connector and variant sitting on hose couplings (Amphenol). – Source: KB

Besides power transmission, the ECP-System comprises powerline data-communication relying on the Echelon PLT-22 transceiver. This system supports data rates up to 5.4Kbps and is designed for even longer freight trains according to AAR standards. Although the data rate is smaller than e.g. Lowspeed CAN (125Kbps, max 500m) it is sufficient for brake control applications as well as other control or monitoring functions which could in the future be typically implemented on freight cars.

4.2 Application: Reefer Power Supply

Besides the low-power electronic applications, there is a higher power demand for refrigeration purposes of reefer semi-trailers on intermodal trains.

Today's transport refrigeration units (TRUs) for semi-trailers such as Thermo King "SLXe", Schmitz Cargobull 'S.KO Cool' or Carrier 'Vector' can be fed electrically in standby operation mode while being parked or for operation aboard a ship. When not connected to an electric power supply, the primary power source consists of a built-in diesel genset.

To operate these refrigeration units without running their built-in diesel engines aboard an intermodal freight train, an electric power supply system has to be conceived and fitted to the train.

4.2.1 Intermodal train scheme

It is assumed that a train consists of two identical groups of wagons. Each group comprises two extremity articulated wagons (UIC 1) with 5 intermediate articulated wagons (UIC 2) in between. All wagons are linked by drawbars – only the intermediate wagons have standard couplings with buffers. A total of 14 semi-trailers can be accommodated by each group of wagons. Each group of wagons has a total length of 232m. Technical data is given by Figure 31 and Table 17.

The Lohr UIC wagons are characterized by a horizontal loading mechanism. The loading pocket is rotated and the semi-trailer can be loaded and unloaded by a regular tractor. This makes intermodal transport accessible for all non-cranable semi-trailers which account for ~97% of all semi-trailers.

	UIC I	UIC 2	UIC 3
Wagon type	Extremity wagon	Intermediate wagon	Individual wagon
Coupling type end 1	Standard coupling with buffers	Coupling bar	Standard coupling with buffers
Coupling type end 2	Coupling bar	Coupling bar	Standard coupling with buffers
Total length	33,87 m	32,94 m	34,80 m
Unloaded weight	41,7 t	40,7 t	42,7 t
Payload	75,3 t	76,3 t	77,3 t
Maximum load per semi-trailer	38 t		
Minimum turning radius	135 m		
Low gauge	UIC 505-1 - GIC2 (EN 15273-1)		
Maximum floor height compared with the rail	225 mm		
Min-max height of the semi-trailer kingpin	870 - 1170 mm		

Table 17: Lohr UIC wagons for semi-trailers. – Source: Lohr
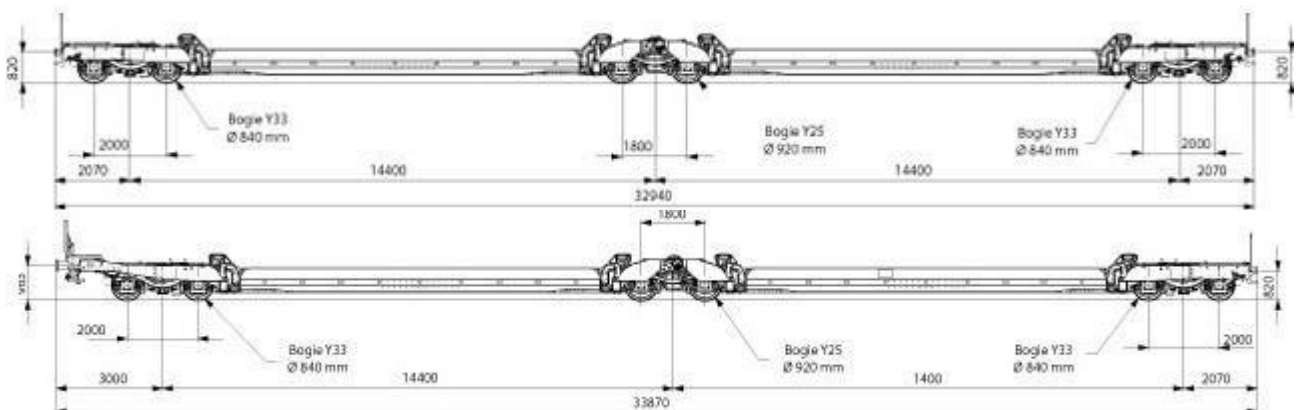
Figure 31: Lohr UIC wagon types. – Source: Lohr
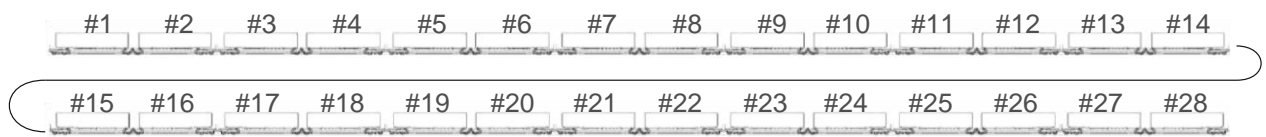
Figure 32: Intermodal train scheme. – Source: Lohr

4.2.2 Transport Refrigeration Units specification

TRUs in Europe are mainly manufactured by Carrier, Thermo King and Schmitz Cargobull . They are equipped with a 32A CEE power inlet according to IEC 60309. Hence they require a feeding 32A CEE outlet equipped with a (30mA) differential protection.[1]

Figure 33: Transport Refrigeration Units for semi-trailers. – Source: Knorr Bremse

As stated by the technical data provided by **Table 18** and **Table 19**, the nominal power of the electric standby motor is ranging from 5.5kW to 23kW. For Schmitz Cargobull TRUs no related information could be retrieved.

Refrigeration CapacitySystem net cooling capacity under A.T.P. Conditions at 30° C ambient	
Capacity on engine power 0°C	13500 W
Capacity on engine power -20°C	7500 W
Capacity on electrical stand by 0°C	10500 W
Capacity on electrical stand by -20°C	5900 W

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[1] VECTOR RANGE – 1550 & 1550 City / 1850 & 1850 Mt° - OPERATING INSTRUCTIONS

Table 18: Thermo King SLXi -200 specifications as an example. – Source: Thermo King

Specification	VECTOR 1350	VECTOR 1550	VECTOR 1950
Cooling capacity on electrical standby - 0°C / +30°C	8000W	13200W	15400
Electric Standby Motor Nominal Power	5,5kW	16kW	23kW

Table 19: Carrier TransicoldVECTOR TRU specifications. – Source: Carrier

4.2.3 Power demand estimation

The actual electric power demand is usually lower than the nominal motor power and is dependent of the actual refrigeration demand. No details referring to the refrigeration power control were given.

For the dimensioning of electric supply networks and their feeding systems usually a coincidence factor resp. simultaneity factor according to IEC60050 is used.

Coincidence factor: the ratio, expressed as a numerical value or as a percentage, of the simultaneous maximum demand of a group of electrical appliances or consumers within a specified period, to the sum of their individual maximum demands within the same period. As per this definition, the value is always <= 1 and can be expressed as a percentage.[2]

(Diversity factor: the reciprocal of the coincidence factor. It means it will always be >= 1.) The applicable coincidence factor is usually given by tables representing heuristic values. In the present case these guidelines are not given.

As a worst-case scenario, each articulated wagon is loaded with a high-power TRU (Carrier Vector 1950, 23kW nominal standby power) and maximum refrigeration demand resulting in a permanent total demand of 14 x 23kW = 322kW for each part of the train.

In a good case, just 50% of all wagons are loaded with TRUs with an average nominal power demand of 12kW and medium refrigeration demand resulting in a total demand of 7 x 12kW = 84kW for each part of the train which represents just 26% of the worst-case value.

On the other hand, there is a necessity to install an economic supply system to the train. For cost and handling reasons, the supply system should rely on multi-core cables and industrial multi-core connectors. As long as no specific requirements are known, the cables specification should meet railway standards. Based on these assumptions, two different cabling/connector systems can be proposed in the following.

4.2.4 Cable/Connector System Proposals

4.2.4.1 125A Cable/Connector System according to IEC60309

As described above, the TRUs are equipped with a 32A-version of power inlets according to IEC60309. Besides the 32A-rating of the plug/socket-system there are also versions for 16A, 63A and 125A.

One 125A connection could be used for the supply of each group of 14 wagons. The maximum apparent power transferrable is:

$$P_{el,a} = \sqrt{3} * 400V * 125A = 86,6kVA$$

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[2] http://www.electrical-installation.org/enwiki/Estimation_of_actual_maximum_kVA_demand

125A connectors e.g. manufactured by Mennekes are available in 4 or 5-pole versions. The connectors can accommodate multi-core cables with a cross section of up to 50mm².

Figure 34: Connector according to IEC60309. – Source: Knorr Bremse

To estimate the voltage drop on a supply line of that kind, the total load is assumed to be concentrated at the middle of the trailing train section. The total length is estimated by the 1.2-fold of the train length which results in 556m. The feeding distance consequently is 75% resulting in 417m.

For copper, the specific conductivity is given by $\chi = 56 \frac{m}{\Omega \text{mm}^2}$.. The voltage drop at maximum rated current results in:

$$\Delta U = \frac{\sqrt{3} * I * L}{\chi * S} = \frac{\sqrt{3} * 125A * 417m}{\frac{56m}{\Omega mm^2} * 50mm^2} = 31{,}2V$$

which equals in 8%.

For standard induction motors according to IEC / EN 60034-1 the allowable voltage fluctuation is +/- 5%. This value reflects the permissible temperature rise of fully loaded motors at maximum ambient temperature of 40°C. Depending of the TRUs design, it can be assumed that there is a certain margin because for a given compressor shaft torque, the next larger nominal torque motor size is selected. It can also be pointed out that a portion of the voltage drop can be compensated by feeding the line with a 5% elevated voltage. As feeder a dedicate inverter is assumed. In most cases the maximum inverter output voltage ranges above 400V. Alternatively, the feeding frequency is reduced depending on the total load down to 46Hz keeping the feeding voltage constant, if this operating frequency is well within the TRU's specification.

Assuming a power factor of 0.9 which is common for IE3 industrial motors in the power range of 3 to 37kW, the apparent power at 125A is

$$\sqrt{3} * (400V - \overline{21V}) * 125A = 79{,}8kVA$$

With an effective power of

$$78{,}8kVA * 0.9 = 71.9kW$$

This would be sufficient to satisfy an average power demand of 71.9kW/14TRUs = 5.1kW/TRU. This reflects just the lower end of the TRU's power range. For a satisfactory operation, it is therefore necessary, either to limit the total TRU power connected to the train supply line for transportation or to introduce a power management scheme distributing the available power to a subset of TRUs.

4.2.4.2 High current cable/connector system similar to IEC EN 60309-1

Rauscher &Stoecklin AG[3] as well as Mennekes[4] are offering a range of connectors for the 200A- 400A range with a design similar to the one according to IEC EN 60309-1.

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[3] http://www.raustoc.ch/Hochstromsteckkontakte.aspx
[4] http://www.mennekes.de

Figure 35: Rauscher &Stoecklin C-Line Connector. – Source: Knorr Bremse

These connectors can accommodate multi-core cables up to 150mm² of each stranded conductor.
At this place, some restrictions related to the choice of cables apply. When screening the catalogues of major European cable suppliers for railway qualified power supply cables (Caledonian, Lapp, Dätwyler, Prysmian, Leoni, Huber &Suhner, Draka), Huber &Suhner is supplying the most comprehensive range of cables. The largest multi-core cable according to the 2016 'Railway Products' catalogue is a *RADOX® 4 GKW-AX 1800V MM S* four-core 3x95mm² + 10mm² cable. A reduced cross-section of 10mm² for the neutral conductor seems so be appropriate since the neutral current is assumed to be comparatively small.
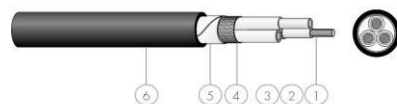
Construction	Conductor	Core	Screen		Cable	Conductor resistance		Z_T	Weight		Item no.
n × mm²	$D_{nom.}$ mm	$D_{nom.}$ mm	$D_{max.}$ mm	Size mm²	D mm	Conductor R_{20} max. Ω/km	Screen R_{20} max. Ω/km	max. m Ω/M	Copper kg/100 m	Cable kg/100 m	
3 × 95 + 10	12.8 3.90	17.5 6.40	39.6	40.8	46.7 ± 0.7	0.21 1.95	0.7	40	291	438	12559402

Figure 36: RADOX 4 GKW-AX1800V cable specification. – Source:Radox

A 95mm² multi-core cable for extended temperature range (electron beam crosslinked insulation) is rated for 250A permanent load according to DIN EN 50565-1 when mounted on a surface.
The associated voltage drop at 250A for a 417m line is accordingly:

$$\Delta U = \frac{\sqrt{3} * I * L}{\chi * S} = \frac{\sqrt{3} * 250A * 417m}{\frac{56m}{\Omega mm^2} * 95mm^2} = 33{,}9V$$

This is equal to 8.4%.

With respect to the 125A connectors described above, the transferrable effective power accordingly can be doubled to

$$2 * 71.9 kW = 143,8 kW$$ This means 10.2kW per TRU.

Without further investigation this seems to be sufficient for most situations. But not all hypothetical cases can be covered. Unless there is evidence, that the total power is sufficient in all cases, some further load-limiting counter-measures have to be foreseen.

4.2.4.3 Load management

A central load management by a dedicate inverter feeding a supply line, is only possible by variation of voltage and frequency, basically keeping the ratio of voltage and frequency constant. In case of motor loads with a velocity-depending load characteristic such as fans and pumps, the load current can be effectively reduced by a lower frequency and shaft velocity.

In case of a TRU, there are several internal loads: Refrigerant compressor, condenser fan and control electronics. Assuming the compressor's and the fan's motors are directly fed without any separate converter, the compressor usually constitutes a constant load characteristics i.e. shaft torque and consequently motor current are virtually unaffected by frequency variations. The condenser fan usually has a parabolic load characteristic, meaning that shaft torque and motor current are over-proportional reduced when reducing the feeding frequency. The control electronics is assumed to be of a constant power characteristic. This means, that a voltage reduction even results in a surge of the load current. Usually the compressor motor accounts for the largest portion of power consumed by the TRU. Because it does not contribute to a current reduction the total system behavior at reduced voltage and frequency is unknown, this method of globally influencing the load on a supply line is considered to be inappropriate.

A decentral load management would require a control unit for each 32A branch line comprising a current sensing unit, a three-phase relay and some control logic which is networked with all other load management units attached to the same feeding line.
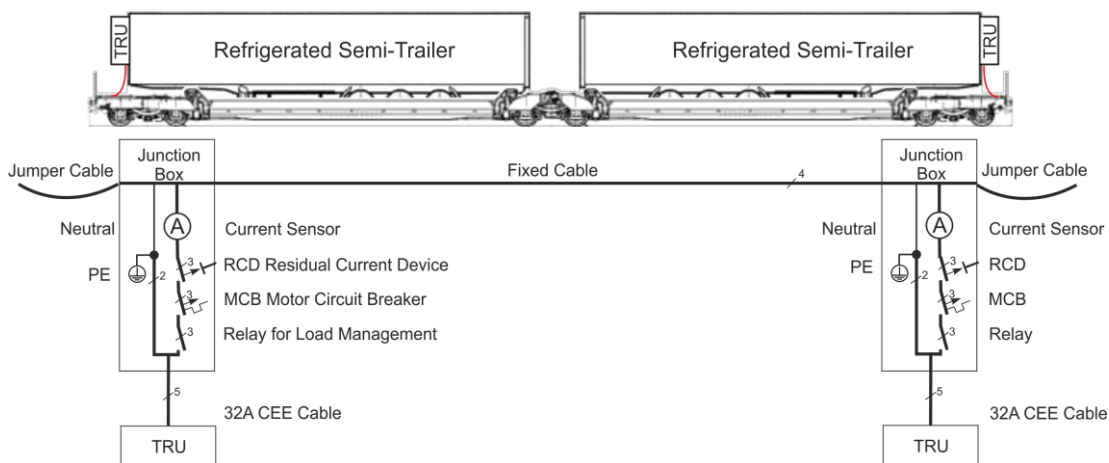
Figure 37: Wagon schematics for load management. – Source: Knorr Bremse

Figure **37** depicts the power schematics without control logic and inter-wagon communication for a decentralized load management. The networked control logic can be implemented in a master-slave structure or in a multi-master structure. A dedicate Jumper cable for the connection of two articulated wagons could be necessary, as the RADOX 4 GKW cable is designed for only for sporadic movement only. A special Jumper version of that type of cable type is available for continuous movement and torsion loads upon request.

As a third measure to prevent overloading of the supply line, a manual loading instruction can be considered. Therefore a total of not more than 144kW of nominal standby power may be attached to each supply line. This requires a clear indication of the standby power consumption on each TRU to be connected. Some dispositive conflict management may be required if there are more TRUs to connect. An alternative could be to allow diesel operation for a small amount of TRUs not connected to the electric supply.

4.2.5 Earthing

Some attention has to be paid to the earthing system[5] of the supply line. For availability reasons, railway auxiliary power supply networks are implemented as IT networks. This means, they are not equipped with a neutral (N) conductor and a protective earth (PE) conductor. The phase's potential is floating with respect to the ground potential. Operation can continue in case of a short of one phase to ground. In this case, the voltage of the other phases versus ground is virtually doubled and all connected loads have to cope with this mode of operation. Furthermore the phase's insulation versus ground has to be permanently surveyed.

Stationary electric supply networks are implemented as TN networks comprising a neutral conductor and a protective earth conductor at ground potential mainly for safety reasons. The TRUs standby feeding is designed for a connection to TN networks.

Due to the difference of the floating potential of the IT network and the symmetric grounded TN system, a galvanic insulation is inevitable. This can be realized on two ways:

- The feeding auxiliary converter is connected to a dedicated secondary winding of the main transformer. The converter needs a neutral connection at 50% DC-Link voltage and is therefore preferably implemented as a multi-level-inverter.

- There is a transformer for both galvanic insulation and for the establishment of a neutral star point between auxiliary converter and the feeding line. The vector group of the transformer has to be chosen accordingly to load on the neutral conductor.

The feeding line on the train is then a four-core-cable with combined Neutral and Protective Earth conductor (TN-C), which is permissible for copper conductors of at least 10mm². Each 32A branch line would be attached via a junction box mounted to the wagon. There an additional Protective Earth (PE) conductor connected to the wagon steel structure. This constitutes a TN-C-S system on the train.

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[5]
https://en.wikipedia.org/wiki/Earthing_system
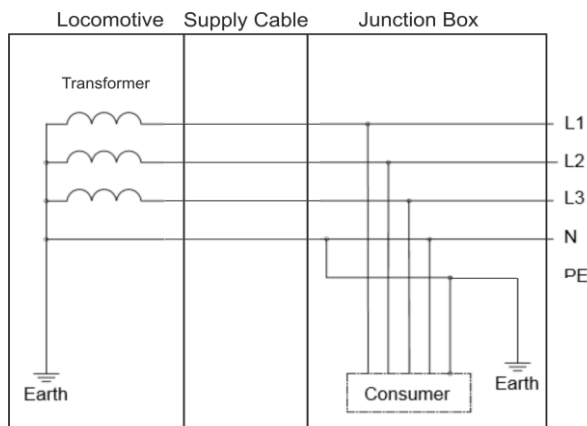
Towards subsequent
Junction Box

Figure 38: TN-C-S system. – Source: Knorr Bremse

4.2.6 Cabling scheme

Figure 39 depicts the proposed dual-line cabling scheme. A dedicated straight cable is feeding the trailing section of the train, while a second cable serves as a distribution cable feeding the TRU supply branches.
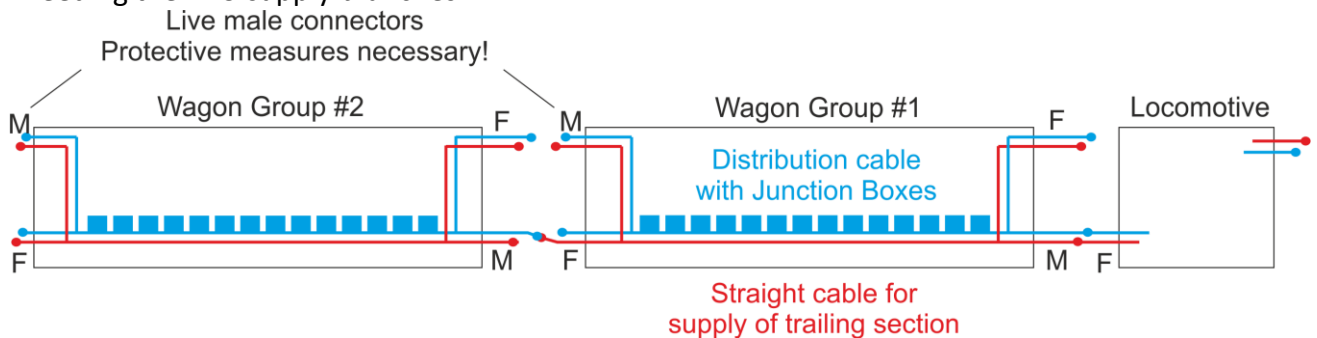
Figure 39: Cabling scheme. – Source: Knorr Bremse

For flexible operation in each direction an each possible train configuration, four connectors have to be foreseen at each train section extremity. Special care has to be taken for the live male connectors. Preferably, a relay is isolating the connectors when not mated. The mated state is sensed via a pair of pilot contacts.

4.3 Decentralized Power Generation (Energy Harvesting)

For decentralized power generation, two solutions are common. Both exert a small braking torque to a wheelset and convert the braking power into electrical power. Finally this is a kind of mechanical power transmission from the locomotive to the wagon.

Electric power can only be supplied while the wagon is moving i.e. the wheelset is rotating. The amount of electric power is furthermore limited by the rotating speed of the wheelset at low speeds and by the nominal power of the generator at high speeds.

4.3.1 Axle Generator
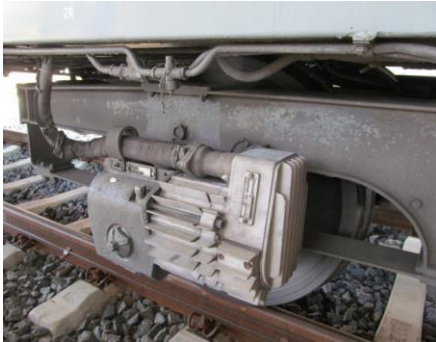
Figure 40: Axle generator fitted to passenger car. – Source: Knorr Bremse

Existing axle generators for 24V DC can supply electric power up to 4.5kW depending on their type. For air-conditioned passenger coaches, there exist also 110V DC generators up to 25kW. In locomotive-hauled passenger services, these solutions are outdated and mostly replaced by UIC 522 central power supply systems.

Remark: The innovation project 'Electric-powered Energy-Efficient Trailer – E³Trail'[6] investigated in axle generators for refrigerated semitrailers in on-road operation.

4.3.2 Axle Box Generator

For low power demands in the range of 10W…100W the following generators, which are directly mounted onto the axle box are available:

Figure 41: Keschwari Electronic Systems Axle Generator 24V, 4A (~100W)[1]. – Source: Keschwari

Figure 42: PJM WagonTracker (>10W)[1]. – Source: Knorr Bremse

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[6] https://www.tu-braunschweig.de/imn/forschung/projekte/for014

Figure 43: SchaefflerAxlebox Generator 24V, 4A (~100W)[1] . – Source: Schaeffler

Equipping a four-axle wagon with a maximum of eight generators at each axle box, the maximum power is ~800W.

4.4 Decentral Power Storage

In combination with decentral power generation means according to section 4.3, a electric energy storage might be required for certain applications, which require electric power supply in standstill and at low vehicle speeds.

Today NiMH or Li-Ion batteries are widely used in a high multitude of applications. Battery packs consist of an arrangement of individual cells in series and/or parallel connection, so that arbitrary storage capacities can be implemented.

Usually, there is a tradeoff between capacity, size, weight, cost, cyclability and temperature range. As battery technology is permanently evolving, no generic solution can be pointed out.

5 Communication basics

Freight Trains in Europe, except some trains for special operation modes, do not have an electro-pneumatic brake system, neither a powerline from locomotive to last wagon for normal electricity applications, nor a wired data communication bus.

To overcome this different scenarios have to be taken into account.

One solution is to bring electricity and a wired data communication bus onto the train (see 3.1)

Another solution is to install wireless solutions for communication either to hop from wagon to wagon (or from wagon x to wagon x+d, where d is a really small positive integer value) or to directly have a wireless communication wagon to loco (or loco to loco) or to have wireless communication intra wagon (e.g. from a sensor to a sensor hub) or to have mobile radio communication (2G, 3G, 4G, in future 5G) from wagon or from loco.

5.1 Wired

Wired communication can be distinguished in classic binary and analogue signal transmission and digital transmission. Both can have multiple transmitters as well as multiple receivers. Digital data transmission allows many different data to be transmitted on a physical connection by making use of serialization, coding schemes and their error sensing and –correction mechanisms as well as time-multiplexing.

5.1.1 Binary

Binary signals distinguish usually only two states on/off resp. high/low. Implemented as a train line, a wired loop is energized by a voltage source. In regular (HIGH) state, a certain load current is present at the loop. Every connected device can open the loop using a relay (LOW). All other connected devices can recognize this toggled state by sensing the missing load current. For this LOW-state, all devices are OR-connected. For the HIGHState, all devices are AND-connected. It is neither possible to determine which device has not toggled the line towards a LOW-state nor is it possible to determine which device is obstructing a pending HIGH-state.

Many applications such as central light- door and electric brake control require just one command-issuing device i.e. the locomotive. In this case, a current loop is not required. A single line with a certain voltage applied or not applied is sufficient to transport centrally issued signals to an arbitrary number of receiving devices on the train.

5.1.2 RS485

RS485 is a generic digital communication standard using the same differential balanced line over twisted pair as RS-422. RS-485 can span distances up to 1,200 m at 100kbit/s. In contrast to RS-422, which has a single driver circuit which cannot be switched off, RS-485 drivers use three-state logic allowing individual transmitters to be deactivated. This allows RS-485 to implement linear bus topologies using only two wires.RS-485 only specifies electrical characteristics of the generator and the receiver. It does not specify or recommend any communications protocol, only the physical layer. Usually a Master-Slave structure is implemented. A Master controller is initiating and scheduling all bus communication.

5.1.3 CAN

A Controller Area Network (CAN) is also based on a differential line over twisted pair. In contrast to RS485 the circuit drivers (transceivers) do not use three-state-logic but support just two states: recessive state and dominant state. In contrast to RS-485 CAN is organized as a multi-master network by making use of a CSMA-CA bus arbitration scheme. The transferrable data rate is dependent of the bus length. Distances up to 500m can be covered at transmission rates of 125 kbit/s. This limitation imposes the need for repeaters for longer freight trains. The CAN specification is covering the ISO/OSI layers 1 and 2. CAN specifies a frame-oriented data transmission including a prioritizing arbitration ID, a data container for up to 64bit of payload and a CRC-error checking field. Higher ISO/OSI-levels are standardized e.g. by CANopen or J1939 and others.

5.1.4 WTB/MVB

WTB and MVB are parts of the IEC / UIC Train Communication Network (TCN).The Multifunction Vehicle Bus is specified for a data rate of 1.5 Mbit/s and distances of up to 200m. It is designed for use on a single vehicle or trains with a fixed configuration (consists). The Wire Train Bus (WTB) is targeted for open trains with variable composition, such as UIC trains. It is covering distances up to 860m, may serve up to 32 nodes and is operated at a data rate of 1Mbit/s over shielded twisted-pair wires. A special inauguration process assigns each node its sequential address and orientation. A standard UIC jumper cable according to UIC 558 is used.

There is a deterministic TCN protocol specified which is handling periodic transmission of time-critical process-variables as well as demand-driven messages. Besides that a network management protocol is specified.

5.1.5 LON

For LON power line communication providing power supply and serial data communication on a single pair of wires see section 4.1.3.

5.1.6 Ethernet

Ethernet is a networking standard originally used for office-and datacenter communication. IEEE 802.3 is standardizing several physical media, such as coaxial cables, fiber optic media and twisted-pair cables. Like CAN ISO/OSI-levels 1 and 2 are covered.
IEC-61375-2-5 is standardizing Ethernet as an alternative trainwide communication backbone bus.
Ethernet is regarded as a future standard due to its widespread use in office and datacenterit which is extending in industrial applications as well as in automotive onboard communication networks. It is well aligned with a huge variety of higher-level-internet protocols enabling a seamless integration of connected devices into global networks and enabling the IoT.

5.2 Wireless Communication

5.2.1 Interesting Communication Protocols

5.2.1.1 RFID
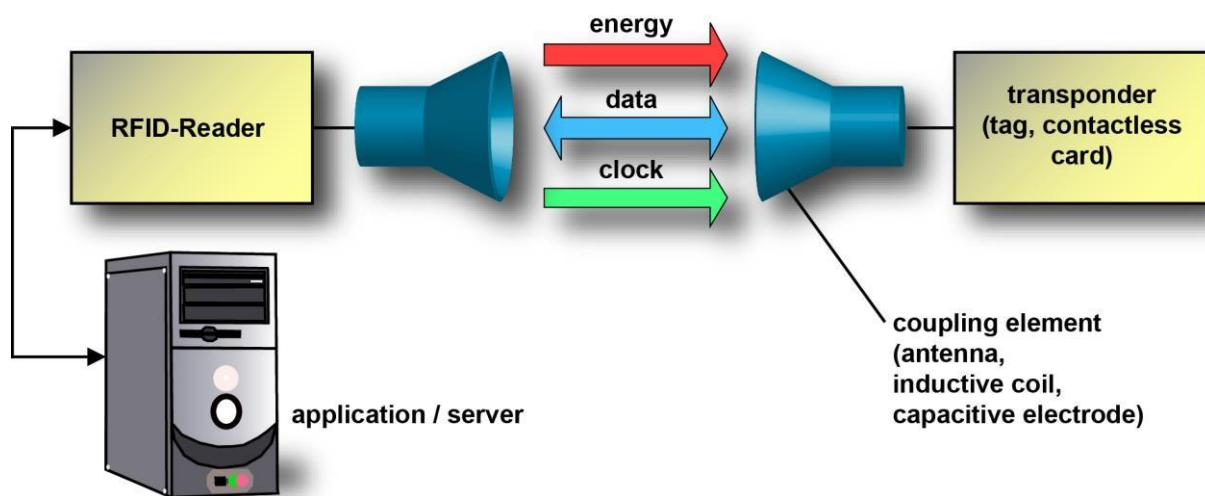
Figure 44: RFID Technology. – Source: Knorr Bremse

Classification
Type
Active (battery/accumulator/energy harvester)
Passive (energy comes from reader antenna)
Frequency
125 kHz   (up to 1 m)
13,56 MHz   (up to 1,7 m)

860 – 958 MHz   (up to 6 m for passive tag)

2,4 GHz   (up to 6 m for passive tag)

Data Storage

Read Only

Read / Write

Write Once
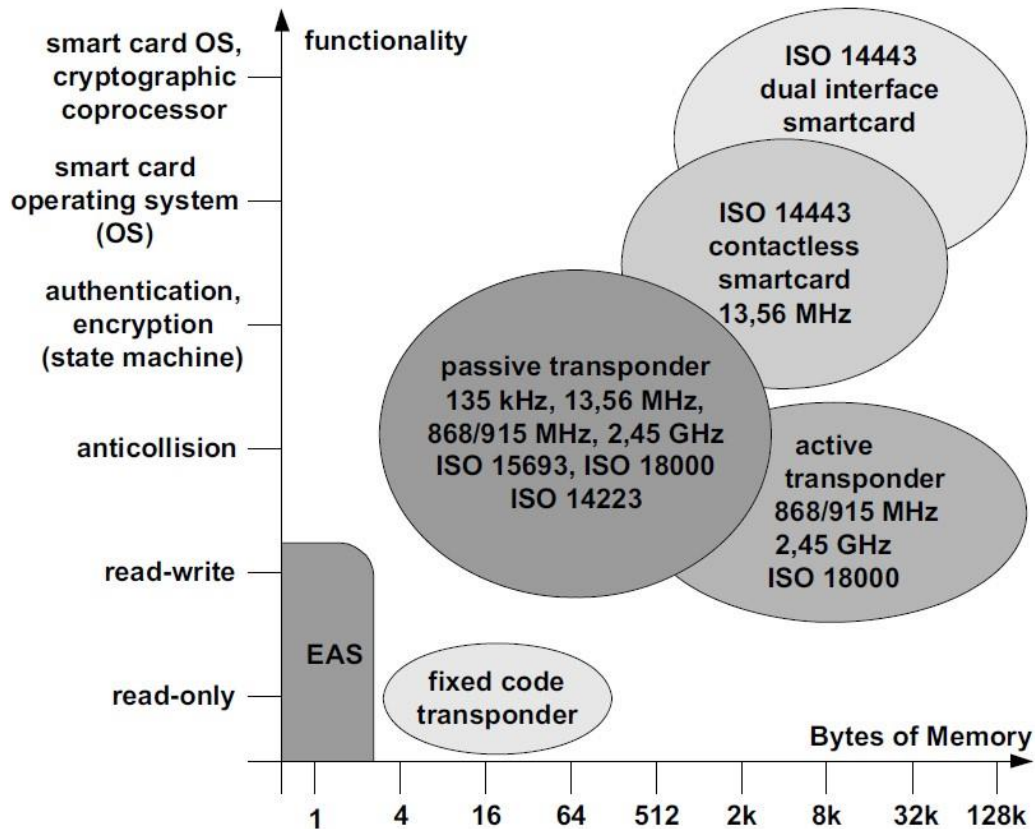
Figure 45: RFID Functionality and Storage Capacity. – Source: Knorr Bremse

EAS = Electronic Article Surveillance Systems (1 bit)

5.2.1.2 TETRA

TETRA (TErrestrail Trunked RAdio) is a professional mobile communication system designed for use by government agencies, public safety networks and the military. TETRA provides robust and secured communication even under disaster conditions.

TETRA was primarily designed to provide voice communication for challenging scenarios, but it includes data communication TETRA operates in the UHF band, which provides favourable propagation conditions compared to higher frequency bands.

TETRA supports data communication like Short Data Service (SDS). This is done in directmode-operation (DMO), because it does not need infrastructure, because the partners can communicate directly. This is interesting for train-to-train communications with point-topoint and multicast (point-to-multipoint) connections.

TETRA is suited for train-to-train communication: Operation possible at highspeed of over 400 km/h
>   Point-to-point and multicast direct communication
>   Low carrier frequencies in UHF band permit a communication range of several kilometres
>   Very fast setup times of typically less than 250ms for a single node call
>   The system contains mechanisms to ensure communication even during overload situations.

This shows that TETRA is a candidate for radio communication in railway.

5.2.1.3 WLAN (802.11)

IEEE standardized 802.11 wireless LAN (WLAN) is a widespread technology for industrial, office and home based radio communication, where performance and response time is essential.

However, this performance does not come for free. WLAN is not energy efficient in the sense of railway applications on non-electrified freight trains. Every smartphone user knows that excessive use of WLAN together with high-performance apps leads to a situation, where charging is required even in less than 24 hours.

One of the real success factors of WLAN was in the past, that the 2.4 GHz band is almost all over the world available for WLAN and license-free. Today WLAN is also available in the 5 GHz band.

In the 1990s, in the 2000s and in the last years as well under the hood of 802.11 additional standards with enhanced feature set were defined. The newest one, 802.11ay is announced for 2017 and offers in the 60 GHz band a stream data rate up to 100 Gbit/s.

WLAN is based on LAN standards, which were described in various 802.X Standards. LAN is often in daily communication called "Ethernet". The wireless variant named WLAN was then specified in 802.11 standards.

The main use of WLAN today, is to transmit IP-packets on layer 3 of the OSI-model.
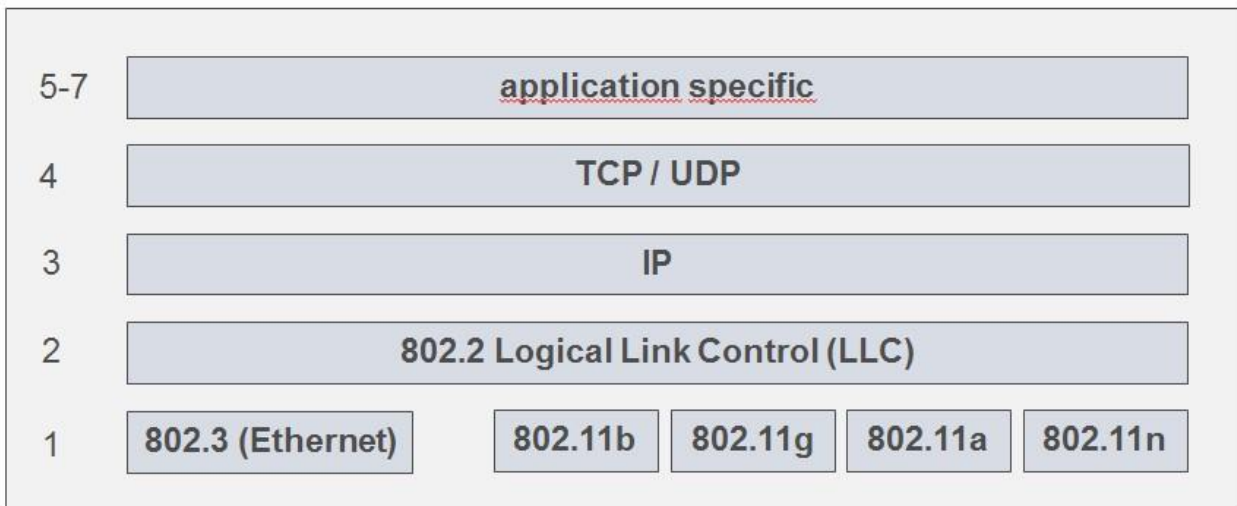
Figure 46: WLAN protocol stack. – Source: Knorr Bremse

Also very well-known is layer 4, where either TCP (connection-oriented) or UDP (connectionless) are common used protocols. Layer 2 was adapted to wireless communication. The main difference is layer one, which was developed completely anew to be able to use radio communication instead of cables for data transmission.

5.2.1.4 Energy Efficient 802.15.4

The IEEE 802.15.4 standard proposes a low data rate solution with longer battery life and very low complexity. This helps in hardware to keep a low PCB foot print, there by leading to miniature communication devices. It specifies the physical layer and media access control for a low-rate wireless personal area network (LR-WPAN). In addition to the proposed Personal Area Network (PAN) it provides constellation based approach to increase QoS and decrease interference. The basic framework of the IEEE 802.15.4 conceives a 10-meter communication area with a transfer rate of 250 Kbps at 2.4 GHz. Its potential applications are sensor networks, toys, remote controls, and home automation. IEEE 802.15.4 devices are characterized by short range, low bit rate, low power, and low cost. This standard is the basis for ZigBee, Wireless HART, 6LoWPAN, and ISA-100, each of which further attempts to offer a complete networking solution by developing the upper communication or application layer.

5.2.1.4.1 WirelessHART

- WirelessHART is based on the IEEE 802.15.4 physical layer and uses 15 different channels. Xx shows the OSI layers of WirelessHART.

- This standard uses the Time Synchronized Mesh Protocol (TSMP), which was developed by Dust Networks for medium access control and network layer functions. TSMP uses TDMA (Time Division Multiple Access) for channel access and allows channel hopping and channel blacklisting at the network layer:

HART

Command Oriented. Predefined Data Types and Application Procedures		
Auto-Segmented transfer of large data sets. Reliable stream transport		
	Redundant Paths Mesh Network	
Byte Oriented, Token, Master/Slave Protocol	TDMA, Channel Hopping	
	IEEE 802.15.4	
Analog & Digital Signaling 4-20mA	IEEE 802.15.4 (2,4GHz)	
Wired (FSK/PSK/RS485)	**Wireless 2.4 GHz**	
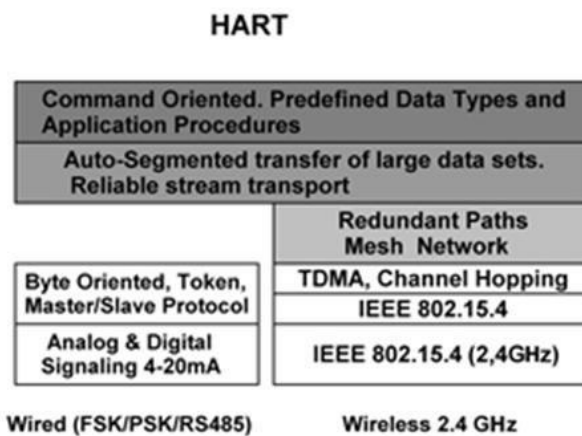
Figure 47: OSI layers of WirelessHART. – Source: Knorr Bremse

- Regarding network topologies, WirelessHART supports star and mesh topologies with redundant routing in order to enhance reliability. All nodes in a WirelessHART networks are routing devices. Xx shows an example of this type of networks.

- WirelessHART is thus considered to be robust, energy efficient and reliable, but since this is still an emerging standard, there is a lot of scope for improvement. WirelessHART was designed, developed and standardized with industrial systems in mind and supports legacy systems built on wired HART.
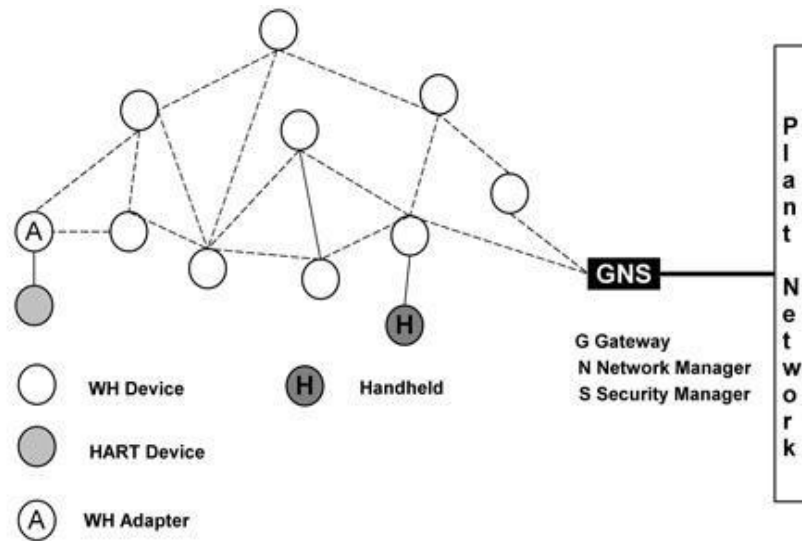
Figure 48: WirelessHART network topology. – Source: Knorr Bremse

WirelessHART, is like any other 802.15.4 protocol suited for energy-efficient scenarios in railway freight.

This protocol is used if we have to convert a wired network into wireless network within a less span of time. This was founded by HART foundation. It uses time synchronized mesh architecture. The advantage is one can gain benefits of wireless technology while maintaining compatibility with existing devices and systems. It provides robust network for process management and asset management application.

5.2.1.4.2 Zigbee

ZigBee is a low-cost, Low Power wireless mesh network. The low network latency of ZigBee makes it very power efficient. ZigBee chips are typically integrated with radios and with microcontrollers that have between 60-256 KB flash memory. ZigBee being very popular is licensed in different band frequencies around the world. ZigBee assists in creating ad-hoc and mesh networking protocol as well. Application and Transport layer can again be added to ZigBee to make it more powerful. ZigBee also comes with built in encryption.

5.2.1.4.3 6loWPAN

The Internet Protocol version 6 (IPv6) over Low power Wireless Personal Area Networks (6LoWPAN) allows IPv6 packets to be sent and received over IEEE 802.15.4 based networks through encapsulation and header compression mechanisms. 6LoWPAN brings IP to the smallest of devices, such as sensors and controllers. The 6LoWPAN protocol is targeted at wireless IP networking applications.The advantage of using 6LowPAN is we can directly convert the existing TCP and UDP data into a wireless data because all the data is encapsulated and no physical modification of data will be done.

5.2.1.4.4 ISA-100.11a

This standard is mainly used for Industrial applications. This standard defines a protocol suite with specific security requirements and power requirements. There is no much change in components and header versions in this protocols when compared to standard based on IEEE 802.11x. People use ISA-100.11a mainly for communication in process control and related applications.

5.2.1.5 IEEE 802.11 (WLAN or Wi-Fi)

Very popular in the world Wi-Fi uses wireless waves in frequencies 2.4GHz and 5GHz for Local Area Network. The certified products produced by Wi-Fi Alliance spread to the world quickly there by making Wi-Fi access on Local network very easy. The widely used is 802.11b standard with 11 Mbps data transfer rate. Since this is a perfect mesh and generally useful for high data rate and large data applications it is very popular for residential, business and industrial applications for general Local Area Networks.

5.2.1.6 IEEE 802.16 (WiMAX)

WiMAX is a wireless broadband standard for Metropolitan Area Network. This provides a data transfer rate of up to 100 Mbps within 10 GHz and 66GHz. The main application of this is providing internet access to computers using wireless medium but at longer distances. There exists many radio channels and the transmission rate in each channel can exceed 120 Mbps.

These options were considered for the WSN's. To facilitate the data transfer it is important that all the wireless devices stick to one protocol. Sensor Interfaces if standardized, can reduce the cost and time of development. This means a ready-made hardware should act as a bridge between sensors and the wireless protocol. Referencing to all the options given it can be concluded that 6LoWPAN based on wireless IEEE 802.15.4 standard would suit for the WSN system on train. It is also supported by the reason of small payload and easy connectivity of wired and wireless sensors into existing Internet.

5.2.1.7 Bluetooth (Bluetooth Low Energy, new Bluetooth 5.0)

Bluetooth is a short-range wireless communication technology aiming to replace the cables connecting portable and/or fixed devices. Bluetooth technology is robust, low power, and low cost. The basic framework of Bluetooth confines a 1 to 100-meter communication area with a transfer rate of 1 Mbps to 3 Mbps at 2.4 GHz. Bluetooth is mainly used for personal area sensor network and short-range portable personal devices. The IEEE 802.15.1-2002 standard is based on the Bluetooth specifications. Having a very low range and necessity of re-transmission are some of its disadvantages making it unsafe in using for large scale sensor network deployment.

The v4 version of Bluetooth offers two wireless technologies: BR/EDR (Basic Rate / Enhanced Data Rate) and Bluetooth Low Energy (BLE). BLE was created in order to support low-power devices with short data transfers. Those devices which communicate through *classic* Bluetooth and BLE (i.e. dual-mode devices) are called *Bluetooth Smart Ready*, while those which support only BLE (i.e. single-mode devices) are called *Bluetooth Smart*. An example of a *Bluetooth Smart Ready* device could be a laptop computer or a Smartphone, while a *Bluetooth Smart* device would be an equipment with critical low-power operation, such as those using coin cell batteries.

Bluetooth 5.0 was announced in June, 2016. It will quadruple the range, double the speed, and an eight-fold increase in data broadcasting capacity of low energy Bluetooth connections, in addition to adding functionality for connectionless services like locationrelevant information and navigation. It is mainly focused on Internet of Things emerging technology. The release of products is scheduled for late 2016 to early 2017.

5.2.1.8 Project Marathon (Distributed Loco Control, EU Funded Project)

Project Marathon is a real example of application of radio technologies in railway between trains. Project was developed between 2011 and 2014 and the main goal was to prove the feasibility of long trains (up to 1500m) in Europe.

One project goal was to implement a safety based reliable and available radio connection between two locomotives with a maximum distance of 750m

Regarding the radio technology the main goal was to find a reliable data link to Exchange command-control data between 2 locomotives which can be used in all European countries.

Tests were done with different frequencies: 400 MHz, 800 MHz, 2.4 GHz and 5.4 GHz.

Conclusions of this first test were:

Radio losses were mainly in tunnels and 75% of the losses lasted less than 5 seconds.

The target for the radiated output power must be in minimum 5W

Directive antennas according to railway standards must be used

Radio equipment must be multichannel because it will be impossible to coordinate the frequencies between the different countries in Europe. As expected frequencies below 1GHz had poorer results in tunnels

One single channel below 1GHz could assure Marathon functionality (Marathon system can handle without effect radio losses if they last less than 4 seconds) although for a wireless TCMS the better strategy could be to have a redundant channel above 1GHz in order to improve performances in tunnels and also to increase the non-safety data rate.

Due to the high density of bands used in those frequencies, to the lower attenuation, to a higher sensitivity to side bands, the use of specific band pass filters is recommended for frequencies below 1GHz.

Final test of Marathon project was done with two channels: 400MHz and 2.4GHz applying some of the conclusions of the first test. Two locomotives separated 750m were connected via radio and the one in the head of the train (the master) controlled the second one.

Concerning the radio behavior conclusions were:

400 MHz channel had fewer disruptions than 2.4 GHz channel.

Only a few losses with impact in the behavior of the train were detected (losses of more than 3 seconds).

Radio interruptions were always in tunnels or their surroundings.

Disruptions did not happen in both channels at the same time, which demonstrate that frequency diversity is profitable although in some spots cut off happened for both channels at the same time.

Integration on the locomotive lead to some degradation on the 2.4GHz behavior compared to the expected. Therefore some improvements can be expected in performance if the integration is better (type of antenna, filters, cables, *etc*.).

The problem of having several networks working in the same geographical area at the same time must be handled carefully. In Marathon project the inauguration procedure of the network was pointed as a key feature.

MARATHON showed promising results with radio communication. Further evaluation of technology, prototyping, safety assessments and proof of implementations has to be done for a product ready implementation of loco-to-loco communication in railway with a maximum distance of 750 m.

5.2.1.9 GSM-R

GSM-R, Global System for Mobile Communications – Railway or GSM-Railway is an international wireless communications standard for railway communication and applications.

A sub-system of European Rail Traffic Management System (ERTMS), it is used for communication between train and railway regulation control centers. The system is based on GSM and EIRENE –

MORANE specifications which guarantee performance at speeds up to 500 km/h (310 mph), without any communication loss.

GSM-R is built on GSM technology, and benefits from the economies of scale of its GSM technology heritage, aiming at being a cost efficient digital replacement for existing incompatible in-track cable and analogue railway radio networks. The standard is the result years of collaboration between the various European railway companies, with the goal of achieving interoperability using a single communication platform. GSM-R is part of the European Rail Traffic Management System (ERTMS) standard and carries the signaling information directly to the train driver, enabling higher train speeds and traffic density with a high level of safety.

GSM-R is in use for safety based communication loco to train-control equipment. The bandwidth is really limited and GSM-R is no more state-of-the-art technology. These two reasons show that GSM-R is definitely not the right technology for intra-wagon or wagon-toloco communication. Further use of loco-to-ground communication beyond safety communication in signaling (ERTMS) are out of scope

5.2.1.10 GPRS, UMTS and LTE

GPRS (2G), UMTS (3G) and LTE (4G) mobile networks are today's mobile networks with a mobile IP-gateway to the internet with IP-protocol.

Thus these radio technologies are the radio technology to be used in all M2M internet communication scenarios.

As of today GPRS, UMTS and maybe LTE (is still a bit advanced in railway) are mobile radio technologies, when a sensor hub (gateway) in a train or on freight wagon have a data communication path with data transmission based on available mobile network connection. So todays' existing telematics applications on freight wagons, where the data are transmitted to a back office server application and database rely usually on GPRS, UMTS and maybe LTE.

5.2.1.11 5G

5G (5th generation mobile networks or 5th generation wireless systems) are the proposed next major phase of mobile telecommunications standards. 5G planning includes Internet connection speeds faster than current 4G, and other improvements.

Key features of 5G networks will be:

    Data rates of tens of megabits per second for tens of thousands of users

    1 GB per second simultaneously

    Several hundreds of thousands of simultaneous connections for massive wireless sensor network Coverage improved

    Latency reduced significantly compared to LTE

5G networks will come around 2020 in Europe. If you look at the key features, the data rates and the improved communication capabilities may change the way, how the internet of the future will look like. Maybe every sensor node and every controller, computer or mobile device will have a 5G module and will be connected to one big "flat" internet network. This means that maybe local networks with different technologies (described here in this text) may lose importance and market share.

5.2.2 Frequencies

The various frequencies utilized are shown in table 2 here under.

5.2.3 Application Layer Protocols

The WSN architecture and its success also depend on how the Nodes will send data through the selected wireless medium. The topic is still circulating on how Big-Data from sensors are sent and

managed in a server. This draws to an important conclusion that the sensor data should be organized, secure and must make sure certain rules are followed when it reaches the remote server. This is done by selecting a proper application layer protocol. This section of document describes some most widely used application layer protocols. The comparison of all these are given at the end.

5.2.3.1 DDS

The OMG Data-Distribution Service for Real-Time Systems (DDS) is the first open international middleware standard directly addressing publish-subscribe communications for real-time and embedded systems. The DDS standard was formally adopted in 2004 and has been implemented in variety of applications which need high data transfer with predictable low latency. The major applications include Radar Processors, Flying and Land Drones, Combat Management Systems, Air Traffic Management, High Performance Telemetry, Large Scale Supervisory Systems, and Automated Stocks and Options Trading. The DDS specification provides fine-grained control over the real-time behavior, dependability, and performance of DDS applications by means of a rich set of quality services. DDS is a model driven architecture which describe the Data-Centric Communications through models-data sets.The basic communication model of DDS is one of unidirectional data exchange where the applications that publish data "push" the relevant data updates to the local caches of colocated subscribers to the data. This information flow is regulated by QoS contracts implicitly established between the DataWriters and the DataReaders.As per the specification, for a fail proof DDS one must avoid using single point Message brokers. DDS also uses a heartbeat mechanism to keep the messaging channel live. To keep messages aligned with many senders and receivers padding or PAD messages can be used. Stateful and Stateless Implementations for DDS are provided in specification and can be used for development. To add more features for security OMG provides another set of separate specifications.

5.2.3.2 MQTT

MQTT is a machine-to-machine connectivity protocol. It is originally designed as an extremely lightweight publish/subscribe messaging protocol. For small code print and heavy resource constraint hardware this protocol is very useful. MQTT is now an open International standard updated and maintained by OASIS. Since it uses Publish and subscribe model MQTT can support one-to-many messaging service. The Messaging technique is independent of the length of payload. The service type can be specified in MQTT. The message can be re-transmitted based upon the instruction given to the broker. A beacon message is used for reducing unnecessary traffic and a mechanism to inform clients and brokers when there is an abnormal disruption is also implemented. MQTT uses specifically TCP/IP protocol and TLS as transport layer. Extra layer of security can be added with the TLS for secure data transmission. Messages in MQTT are published on topics. There is no need to configure a topic, publishing on it is enough. Topics are treated as a hierarchy, using a slash (/) as a separator. For a message other than text there must be a separate parser tool functioning behind this to extract the data from message.MQTT also provides Username and Password messaging option.Conformance targets allow the Client and Sensor to interact with Web socket interaction increasing the quality of messages sent.

5.2.3.3 CoAP

Constrained Application Protocol (CoAP) is a software protocol intended to be used in very simple electronics devices that allows them to communicate interactively over the Internet. The Internet Protocol Suite is being used more on small devices with severe constraints on power, memory, and

processing resources, creating constrained-node networks and CoAP is designed specifically for this kind of networks.CoAP uses UDP as a default mode of transport, but it can also be converted to use TCP. The interaction model of CoAP is similar to the client-server model of HTTP which also facilitates REST model. However, machine-tomachine interactions typically result in a CoAP implementation acting in both client and server roles. A CoAP request is equivalent to that of HTTP and is sent by a client to request an action (using a Method Code) on a resource (identified by a URI) on a server. The server then sends a response with a Response Code; this response may include a resource representation. These messages are of URI and content –type supportive.While using UDP it can optionally bind and support unicast and multicast requests. This is specifically built for large number of nodes and the issues like congestion control are addressed in the Specification document. Since it features easy HTTP conversion creating a web application using CoAP is not difficult.CoAP facilitates for resource discovery which means a remote node can attach to the network seamlessly. As a default security feature it provides 3072-Bit RSA keys. Despite of complexity,CoAP still runs in hardware with very low code foot print.

5.2.3.4 AMQP

Advanced Message Queuing Protocol is designed to avoid existing middleware. The middleware translates the messages from client to server acting like a broker, which is avoided in AMQP. It is an open Internet Protocol for business messaging. AMQP is divided up into separate layers. At the lowest level a binary peer-to-peer protocol for transporting messages between two processes over a network is defined. At higher level an abstract message format, with fixed standard encoding is defined. Every compliant AMQP process must be able to send and receive messages in this standard encoding. This protocol is dynamic and fits into existing enterprise applications. Token based message exchange can be included to have additional safety regulation on the data. Even though the QoS cannot be specified, the message can be prescribed with proper acknowledgement and return tokens. This messaging platform can use TCP/UDP-Multicast SCTP. The messaging protocol is made to work seamlessly with XML data. AMQP data is connection oriented which leaves us with a doubt of less efficiency when more unreliable networks with lot of congestion try sending the data.

5.2.3.5 XMPP

The Extensible Messaging and Presence Protocol (XMPP) is an open Extensible Markup Language XML protocol for near-real-time messaging, presence, and request-response services. XMPP is generally implemented via a client-server architecture wherein a client utilizing XMPP accesses a server over aconnection, and servers also communicate with each other over TCP connections. An intelligent server provides the abstraction layer, client connect directly to server with a TCP connection. Specifications are also proposed for a Gateway in case there is a data which requires XMPP to non-XMPP conversion. The XMPP demands Connection oriented TCP and an extra Transport Layer Security can be added to provide stream security. This security will prevent plain XML data being dropped, misused or modified. Application specific syntaxes are very much necessary making it difficult for data conversion.

5.2.4 Operating Systems for WSN's

For network protocols to function on hardware, an operating system that implements the protocols runs on every node. The operating system manages the resources on each node, provides a layer of abstraction for the hardware, and gives the system developer a programming interface that allows applications to be efficiently implemented. The severe resource constraints, the diversity in hardware platforms and the novelty in applications make sensor network design a challenge. In a WSN there are

many critical resources like power, memory, size, times and network interfaces. The operating system manages all these resources in a controlled manner. Applications can be written on top of the operating systems using system calls. WSN system utilizes many programs running in the background. The OS may schedule each process in the background multiplexing of resources. If the outputs of Hardware have to be used for multiple purposes OS can also do space multiplexing. An operating system for WSN system should follow some design patterns. With a proper architecture and scalable OS it is possible to put it on an Embedded System.

A remote WSN node will contain a Radio module for wireless communication along with necessary sensor peripherals like Analog to Digital converter (ADC). The microcontroller coordinates these actions by running an Operating system inside it. The remote node will also have a Battery for Power.

5.2.4.1 Features of WSN Operating Systems

5.2.4.1.1 Operating system organization

The organization of an OS composes its architecture. This has an influence on the size of the OS kernel and its way of services to the application programs. In brief OS architectures can be Monolithic architecture, Micro-kernel architecture, Virtual machine architecture and Layered architecture.

In Monolithic architecture each specific function will have a separate module. For a complete system all functions have to be taken together and then put into Hardware. Even though this requires a very small code foot print, it is very difficult to maintain. Application development is also difficult since it is hard to understand and program. The next choice is Micro-Kernel architecture. In here a low foot print OS-Kernel is already provided with necessary functions like I/O access, memory management, timers etc. The application developer has to use these basic features to make the operating system more functional. Micro-Kernel architecture is more reliable because it adapts successfully for a systems with changing requirements.The disadvantage is Micro-Kernels can be slow because of user and kernel interaction. A good hardware with proper bus structure may improve the performance. When WSN's are considered this type of structure is more reliable. Some standard Micro-kernels can be trusted for proper functionality and SDK will be easily available for application programming.Virtual machine architecture practically does not make any sense to WSN because we need another operating system which runs a virtual machine resembling the original hardware. The layered Operating system structure is another form of OS in which services offered by OS is divided into layers. It starts with device access, memory access, File-system and continues. The main disadvantage is that the OS tends to be less efficient than other implementations.

5.2.4.1.2 Multitasking and Scheduling

It is the responsibility of the operating system to use all the resources available neatly in a sharing manner. If an application written for the OS which uses many resources ex. Timers, Interrupts, File System, The CPU should be able to process all these requests. If there is no proper scheduling and execution mechanism the WSN will run slow. To make this happen there is a threading mechanism necessary.Based on priority of application the CPU should determine the application that should be processed. This maximizes the resource utilization and throughput of the system. Memory allocation is another important feature an OS must carry. The OS should be able to do both static and dynamic memory allocation based on the application needs.

5.2.4.1.3 Programming structure

Developing applications on a WSN must follow specific rules. Since there is less memory and less computational power available applications must be intelligent to understand and operate. Two types

of programming techniques are followed for resource critical applications. They are Event Driven and Multithread Programming. Event driven is most useful for resource critical application but for application development it is not very supportive. The event driven programming hardware configuration also plays an important role by providing configurable interrupt services and interrupt scheduling etc. So for a programmer it becomes little difficult to understand, the concept also changes with new hardware. Multi-Threading is not as efficient as Event based but from Programmers perspective it is easy for development. Thereforean operating system with a mixture of both the above mentioned methods is required for WSN System.

5.2.4.1.4 Communication and Network Interface

This is a very important feature that a WSN should have. If a kernel must be configured to handle IP or any other standard communication interface, then the developer has to start from scratch. Instead if OS supports standard communication interface like UART, SPI, Ethernet (MAC) and Radio, the developers can write direct applications without worrying about hardware-software interaction for network interfaces.

5.2.4.2 Available Operating Systems for WSN

Based on the feature sets described in the section above, some operating systems their brief structure and properties are presented.

5.2.4.2.1 TinyOS

TinyOS is an Open source operating system. It is specifically designed for WSN's with low power and low memory. The OS provides software abstractions which can be stored in a flash memory and be used for application development.TinyOS is written in NES C. The OS supports secure networking along with standard Internet Protocol implementations.The TinyOS follows monolithic OS architecture and relatively fast for simple applications.TinyOS doesn't work well with long, uninterrupted pieces of code and CPU-intensive applications can cause problems. Being too much memory and computation intensive it does not support complete multi-threading and other important features of OS. It is an extra job for the developer to make the hardware more reliable which runs TinyOS.

5.2.4.2.2 RIoT

RIoT is an open-source micro-kernel based Operating system. This OS is specifically designed for IoT and WSN's. The kernel in RIoT is mainly based on FireKernel which was specifically designed for sensor networks. RIoT is 8, 16 and 32 bit hardware compliant, which includes hardware independent libraries to be incorporated in a new platform. The OS also supports multi-threading and real time operation. The important feature of this OS is that it supports standard debugging tools like GNU-C and standard POSIX interface. The interfaces make it General OS compliant like Linux or Windows. RIoT offers priority based scheduling which enables timer based sleep and wake modes. This is important when the hardware supports very less number of interrupt services. The clock latency for this scheduling is less than 50 clock cycles. RIoT is specially designed for Content-Centric Networking, which supports options like multi-hop and eases IP-based host oriented message transfer. The coding can be done in both C and C++. For protocol stacks it supports 6LoWPAN, IPv6, RPL, TCP, and UDP.

The application layers like, CoAP and CBOR are in development phase.RIoT projects a zero learning curve for embedded programming; this means the development time for drivers, hardware and application is very less.

5.2.4.2.3 Contiki

Contiki is a lightweight operating system which is also designed for highly resource critical systems. Based on Linux and GCC it offers plenty of features for easy design and Integration. Contiki supports standard IPv6 and IPv4, along withthe recent low-power wireless standards: 6LoWPAN, RPL and CoAP. Contiki provides large set of hardware options for installing and commissioning of WSN.Contiki provides memory allocation, dynamic module loading and a sleepy radio listening module. These features make Contiki robust for low power and low memory hardware's.Contiki provides structured multithreading (PROTOTHREAD) and a dynamic filesystem called as "coffee". For module wireless testing, Contiki also provides a simple wireless protocol stack called as "rime". This can be used for initial development and debugging purposes. Along with the code a network simulator COOJA for Contiki OS is also provided which can be used to simulate the WSN environment.Contiki is implemented in the C language and has been ported to a number of microcontroller architectures, including the Texas Instruments MSP430 and the Atmel AVR.Contiki is being followed by many developers and it also has a standard regression system to check if the code contribution from a developer is error free.

5.2.5 Summary

Please find here a comparison of some wireless protocols

Standards	IEE 802.15.4 Low power personal area network				IEEE 802.15.1 (WPAN)	IEEE 802.11 (WLAN)	IEEE 802.16 (WWAN)
	Zigbee	6lowPAN	Wireless Hart	ISA 100.11a	Bluetooth	Wifi 802.11.a	WiMAX 802.16da
Range	100m	50m			100m	5km	15km
Data rate	250-500Kpbs	250Kbps	250Kpbs	250Kbps	1-3Kbps	1Mbps-450Mbps	75Mbps
Frequency band	2.4Ghz	2.4Ghz	2.4Ghz	2.4Ghz	2.4Ghz	2.4, 3.7, 5 GHz	2.3, 2.5 and 3.5 GHz
Topology	Star, Mesh, Cluster Tree	Star, Mesh, Cluster Tree, IPv6	Star, Mesh, Cluster tree	Star, Mesh, Cluster tree	Star	Star, Tree, P2P	Star, Tree, P2P
Applications	Home automation, sensor monitoring	Wireless Sensor Network with Internet	Process control application, Industrial automation	Home and Industrial automation	Peripheral control and access	Large scale Internet connectivity	Large scale Internet connectivity

Table 20: List of wireless protocols. – Source: Knorr Bremse

With reference to the presented application layer protocols for WSN's a table of briefly compared objects from the protocols are shown in the table below.

Protocol Poperties	Notes/Remarks	Application Layer Protocols				
		DDS	MQTT	CoAP	AMQP	XMPP
Initial membership discovery	is it able to identify itself, when it requires assistance its Partial	Yes	Partial	Yes	Partial	Yes
Merging after network break down	break and connect, in case of power failure, sleep and wake mode	Yes	Partial	Yes	Partial with loss of data	Partial
Failure Detection	Lost packet, lost data detection	Yes	Partial	Yes	No	Partial
Reliable message transmission	QoS, acknowledgement and retransmission	ModifiedQoS	Yes	Yes	No (Broker based data transfer)	No
Message stability	will the message remain in the node until there is a proper retransmission	Partial	Yes	Yes	Yes	Less
Flow control	If sender is fast and receiver is slow?	No	Partial	Yes	Yes	No
Fragmentation	Whether a long data has to be cut into parts before transferring?	No	No	No	No	No
Security	AES or how many bits?	Extra layer	Partial	Available	No	Partial
Compression	Does it Require an extra layer of compression?	No	No	Partial	No	No
Network Activity	Time for which the node must be active	High	Connection Oriented	Connection Oriented	Connection oriented	Connection oriented
Error Control		Yes	Yes	Yes	Partial and Optional	No
Integration with other blocks	It is easy to adapt and integrate this protocol with other layers?	Yes	Yes	Udp, TLS easy	Yes	Yes
Open Source		Yes	Yes	Yes	Yes	Yes
Congestion control	all other nodes should also be able to access network	No	Yes	Yes	Yes (Broker based)	no

Table 21: Comparison of different WSN application layer protocols. – Source: Knorr Bremse

The results from the table favor two protocols for our application on train. These are MQTT and CoAP. A network which is secure by itself and can control congestion by not adding too many headers into the existing data will be chosen for the implementation because of unavailability of too much computational power and not much network space.The effect of middle-wares also has to be taken into account. For example AMQP always requires a middleware which acts as a broker between client and server for data transfer. When it comes to bi-directional implementation, only CoAP can handle it. Since the power conservation is a very important aspect there should also be an opportunity to handle UDP data instead of TCP data. UDP is preferred for low power, highly conservative environment because it is connection less. Proceeding further CoAP will be used for WSN implementation with a reliable hardware and a small and powerful operating system. And finally we have here a comparison of the different operating systems

OS	Minimum RAM	Minimum ROM	Application Language	Hardware Type	Programming Model	Communication Protocol Support	Security	Simulation Support
TinyOS	<1KB	<4KB	Nes C	MCU	Event Driven	Active Message	TinySEC	TOSSIM
Contiki	<2KB	<30KB	C	MCU	ProtoThreads and events	Rime, uIP	ContikiSEC/AES	COOJA
RIoT	~1.5KB	~5KB	C/C++	MCU	Multi-Threading	CCN Lite, uIP	AES	Desvirt

Table 22: Comparison of Operating Systems for WSN. – Source: Knorr Bremse

The large developer base and existence of standard regression system with lot of communication protocol support has given strong points in selecting Contiki operating system for WSN implementation.

6 Technical conclusions and further work

6.1 The impact of synchronous braking on the Wear and Tear

There are straightforward benefits on using EP brakes for vehicle safety, brake time, brake length, etc. However, the benefits on reducing wheel damage when using block brakes are not so obvious, for regular brake to stop, or for emergency braking, where the temperature increase will not justify a substantial improvement in the damage sustained by the wheel threads.

According to some references, for sustained braking at constant speed there can be a temperature of 500°C at the tread is reached after 2000s of brake application. In this case, two practical approaches are employed: i) constant braking or ii) strong braking periods combined with no braking periods. Apparently the second case deals less damage on the wheels. Considering also the lack of empirical data on novel brake block materials, this should definitely be studied more, e.g. in Shift2Rail.

6.2 Wireless Communication

6.2.1 In-train network

Radio communication through train to the locomotive is a more challenging topic than communication intra-wagon.

In principle there are two ways of how communication works.

There is a single link from one wagon to the loco (or from loco to loco in e.g. distributed loco control like in MARATHON)

There is a hop from one wagon to the next (or to the 2nd, 3rd, 4th … wagon, whatever radio technology allows) The advantage of reaching the 2nd, 3rd, … wagon is redundancy even if one node does not work properly or if one legacy wagon is not equipped with a radio node. One disadvantage for radio communication in freight railway is disturbance through a lot of iron and steel and through electro-magnetic radiation.

In a freight railway scenario, where most (all) of the wagons (of a fleet or a mode of operation) are equipped with radio nodes, a hop communication system would be definitely preferred, because there is much redundancy.

A single link from wagon (loco) to loco is challenging in terms of distance (up to more than one kilometer in the future), in terms of disturbance from harsh iron or steel environment, from tunnels, from bridges and other tricky things.

The wireless communication to create an on-train network is to be appreciated according to the status of the stakeholder which belongs mainly to three categories: the wagon owner or keeper, the railway undertaking and the shipper or forwarder or consignee.

The first point that is to be noted is that the idea of a train line by cable is rejected by keepers or RUs because of the incorporation of only one non equipped wagon in the train would interrupt the connection eliminating any positive effect. This means that this cable solution must be limited to shuttle trains operated with captive fleets of wagons. The significant positive impacts have been noted in the US by Norfolk Southern which has equipped 1500 wagons and 700 locomotives with such EP brake with a cable all along the train.

The preferred solution is the wireless train network which allows non equipped wagons to be inserted in the train without reducing to nil the positive effects.

The choice of the wireless solution is based on two factors: the economy of energy and the need of getting information in real time without delays. A second category of parameter of choice is the need of having a high accuracy of the positioning of the wagon when the information is captured.

According to the type of cargo the preferred solution may be the most economical one in terms of energy, low accuracy of the positioning and low frequency of refreshment or a more expensive one in terms of consumption of energy needing a powerful battery helped by energy harvesting to feed an accurate GPS positioning with a frequent refreshment of the data transferred and even a capacity of direct transmission by GSM if the wagon has to remain alone. This last solution is clearly installed for high value goods or highly dangerous goods for which a very precise track and trace system is appropriate.

The in-Train network needs a locomotive equipped with intelligence able to communicate with the intelligence installed on each wagon. This intelligence is concentrated in a smart box which can use the technology LPWA for IoT devices to communicate with the smart box of the locomotive with a very low energy consumption. If the locomotive is not equipped with such a smart box but with a different system then the communication is forwarded to the antennas of the LPWAN or if

necessary to the servers of the base by GSM or similar technologies. The in-Train network of that type is the lowest energy consumption solution available today.

6.2.2 In-wagon network

Inside the freight wagon electrical power is the critical resource. As of today most of the rail freight wagons do not have a powerline from the locomotive, nor an electrical power generator like a diesel motor with electrical generator. A high power battery (accumulator) with a powerful energy harvester (like an axle generator capable of producing in the watt range) is still very expensive and is not yet installed in most of the freight wagons.

This means, for communication intra-wagon an energy efficient radio protocol is required. Especially wireless sensor nodes attached at different places of the wagon rely heavily on an energy efficient radio protocol.

As of today two protocols or protocol families are in the interest of the railway community: 802.15.4
 protocols
 Bluetooth low energy.

Both technologies are energy efficient. Both are able to transmit data intra-wagon. And both protocols have already found widespread use and both have already been tested in prototypes in railway.

There is one problem: The two protocols are not compliant. So you can either use one of the two technologies. A mixed network with 802.15.4 nodes and Bluetooth low energy nodes does not make sense. But today new technologies for IoT devices are the best solutions as they fulfill the main demands: not frequent updates, extremely low energy consumption and restricted volumes of data to be exchanged by device.

Numerous devices may be installed on a wagon to check the status of various components. Connecting by cable these devices to the smart box in charge of transferring, after storage, the informations to the locomotive via the wireless on train network would be quite expensive and the preferred solutions is to use wireless connections of the LPAW typewith an extremely low energy consumption for a very long time use of a battery. The data transferred are limited and the frequency of refreshment is quite low. Most of the equipment that are to be controlled are now and in the future equipped with IoT enabling them to exchange with the Smart Box.

6.2.3 Train to Ground communication

In fact there are two different strategies to cope with train-to-ground communication:

* You use existing radio technology infrastructure for train-to-ground communication. This means you use GSM/GPRS, UMTS, LTE and in future 5G networks for communication. In fact it is not purely using existing infrastructure. The radio network operator will equip along the track (same situation as along the highway) radio base stations to get good coverage and bandwidth along the mobile path (here a railway track)

* You build your own radio transmission infrastructure. This is especially done in urban areas e.g. for metros. For long-distance it is very expensive to cover the whole track with e.g. WLAN routers each one covering only a distance of some hundred meters.

So the technology to choose for railway freight is definitely a radio technology as of today (UMTS and LTE; maybe some legacy systems based on GPRS) and 5G in the future.

If no urgency is required and low quantity of data are to be transferred the simple GSM solution is a cheap solution. If you have a in-train network the energy consumption is no longer a constraint as it is the locomotive that sends the massages to the ground servers for the various stakeholders. The type

of connection is led by the level of safety (GPRS or GSM), the requested frequency of refreshment, the volume of data to be transferred and the cost.

6.2.4 Applications

The German expert group TIS ("TechnischerInnovationskreisSchienengüterverkehr") discussed in 2014, how a reference architecture on freight wagon for intelligent telematics solutions should look like. The following figure was made by Knorr-Bremse (Martin Deuter, KB SfS Rail Innovation) and is now used as generic reference architecture for the intelligent freight wagon of the future.

Key aspects are:

- RFID tag
- Power supply with exchangeable accumulator and optional energy harvester
- Sensor hub
- Wireless telecommunication Module (2G, 3G, 4G)
- Navigation satellite system
- Sensor data processing unit (CPU)
- Data logging unit
- Wired/wireless sensor network
- Radio network / wired network
- Sensors
- Further optional components are a TCMS interface and/or a wireless Train network interface for wagon to loco communication
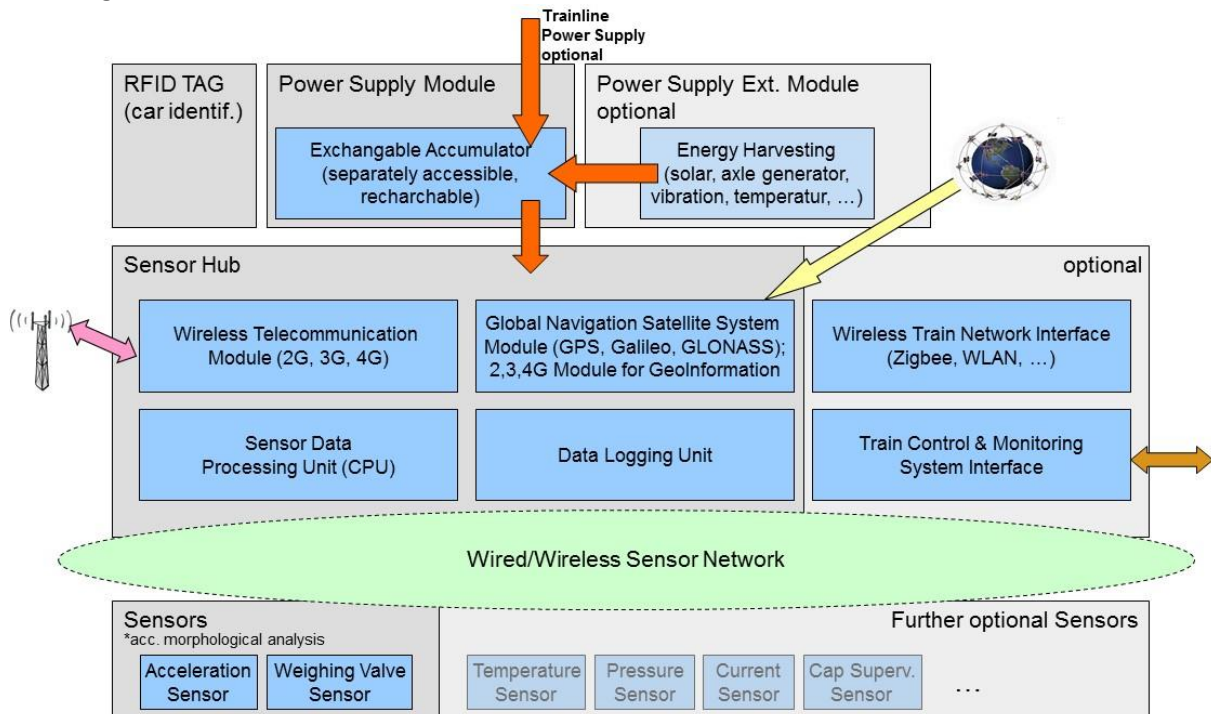
Figure 49: Functional System Architecture for Telematic Applications (according to TIS). – Source: TIS

This analysis is to be updated with the large introduction of IoT technologies using LPWA.
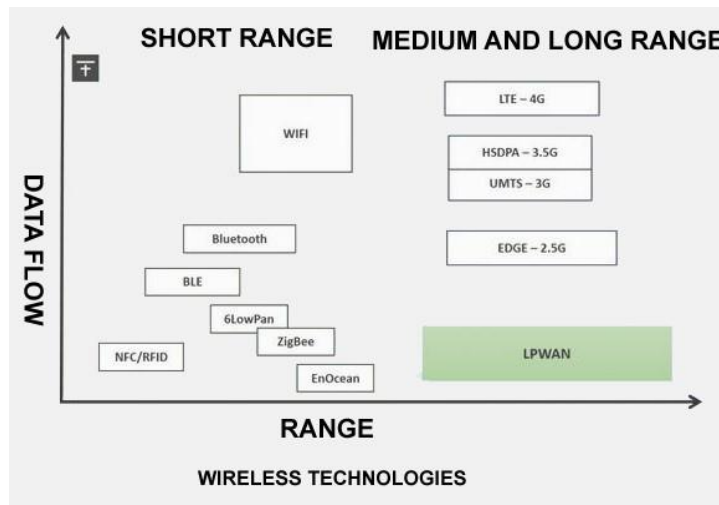
Figure 50: Wireless technologies and data flow diagram. – Source: Newopera

The cost benefit analysis of these solutions for all communications are detailed in section 8.

7 Defining the main KPIs to assess the progress of efficiency

a.   Reminder of the demands of the shippers, forwarders, operators

The main demands are related to reliability and cost reduction. To achieve these objectives we have to define which are the main parameters impacting these main targets.

i.   Reliability is mainly impacted by the technical reliability of the rolling stock and in our case by the reliability of the wagons implying a high level of quality of the maintenance. This may be achieved by the introduction of predictive maintenance.

ii.   Reliability is also extremely dependent on the train management. In this field the question of a full respect of the departure time from the terminal is fundamental. This may be obtained by a very strict organization of the operations on the terminal which is helped by an efficient preparation of the operations. A precise ETA (Estimated Time of Arrival) at the terminal is extremely efficient and for that reason installation of autonomous track and trace devices on the train and the wagons is important with a real transfer of the position information to the interested parties.

iii.   Reliability being dependent on the path quality and on the priority given to the train it has been frequently suggested to increase the freight train speed. But the loss of capacity of transport at a higher speed for safety reasons reserves that solution to very high value products which transport can afford such a reduction of payload in a train. Between 100km/h and 200Km/h the payload is in average reduced from 1200T to 110T.The decrease is near linear in the range from 100km/h to 120km/H , a little more important proportionally until140km/h and then it is no longer linear and the payload drops to 110T at 200km/h. The other solution, besides getting a dedicated freight network or a higher freight priority, is to enhance the maneuverability of the freight trains which may be obtained with synchronous braking and releasing with quick reactions. EP brake solution proposed in the present project has that goal.

iv.   Cost reduction is the result of progress on several parameters:

1. The increase of the usable length enables to reduce the transport cost per meter which may be interesting for light cargo with large volumes.
2. The payload increase reduces also the transport cost per ton
3. The improved flexibility of the type of units which can be loaded improves the asset utilization
4. The better reliability of the equipment improves the overall available time for transport and reduces asset cost per trip.
5. An improved path is equivalent to an average reduction of the transit time and thus reduces the cost of the asset per trip.
6. An improved path reducing the transit time impacts the major cost factor : driver cost.

b. **What KPIs can represent the progress of efficiency in these fields**

i. The normal statistical assessment of the reliability is the ratio between the number of effective fulfillments of the contract divided by the number of application of the contract. This KPI is the result of the efforts made on the various parameters. Some indicators would characterize easily the increased quality of the maintenance: number of incidents for each category of equipment (Rolling stock) divided by the number of kilometers performed.

ii. For the path quality, which is essential to achieve a better reliability it is necessary to appreciate its resilience to incidents.. For that purpose a regular survey of the incidents happening during the trip generating a certain amount of lost minutes at the point of the incident must be put in correlation with the number of minutes lost at the arrival of the trip. The following KPI: (1(number of minutes lost at arrival/number of minutes lost at the point of the incident or incidents)*100%) will represent the capacity of the path and of the train management to recover the difficulties encountered or even a late departure.

iii. For the cost reduction which is the global result of several impacts the possible KPIs are quite classical:

1. The percentage of usable length to place cargo
2. The ratio between the payload and the gross weight of the train measured in percentage
3. The average number of loaded kilometers per year of the wagons
4. The average number of empty kilometers per year of the wagons
5. The average commercial speed of the train divided by the maximum speed allowed of the train
6. The cost of wagon maintenance per kilometer and the cost of maintenance per tonkm transported

All these KPIs would indicate if the results of the innovations enable to progress towards the targets set up by the users and /or their clients.

8 Cost Benefit analysis

8.1 Expected impacts of the various measures and innovations proposed in the project

Without extremely complex simulations on the impact of each innovation on a given traffic on the Rail Network, which are largely beyond the scope of the present project because of its limited resources and its TRL level , the expected impacts will be established on the basis of operational expert's advice.

However for certain KPIs the physical impacts maybe easily assessed on the basis of a 750m train in general but 550m trains for cars:

For the 12 axel wagon carrying swap-bodies the reduction of length is 1,8% which leads to an increase of a carrying capacity of 2 more swap-bodies per train (50 instead of 48)

For the 6 axel and 5 bodies for automotive traffics the impact in term of capacity is depending on the size of finished cars that are to be transported and on the type of present utilized wagons:

Car segments	5 bodies / 6 axles 64,78m x 8 = 518m	2 bodies / 4 axles 30,66m x 17 = 521m	2 bodies / 3 axles 26,50m x 20 = 530m	Difference
< 3,55m	272 cars	238 cars	260 cars	+12%>d> +4,6%
< 3,78m	256 cars	238 cars	240 cars	+16%>d> +6,6%
< 4,05m	240 cars	238 cars	240 cars	=
< 4,35m	224 cars	204 cars	200 cars	+20%>d> +9,8%
< 4,69m	208 cars	204 cars	200 cars	+4%>d> +2%
< 5,10m	192 cars	170 cars	180 cars	+12%>d> +6,6%

Because the precise calculation of the resistance of the wagons in the new optimized design cannot be done within the scope of this project, it seems preferable to reduce a little the length of each body of the New 6 axel- 5 bodies wagon as the reference of the structure are already existing. The impact is a little loss of 2 cars in term of capacity but it gives a side advantage in allowing to reduce the number of Chocks necessary which implies an operating cost reduction. The results are in the following table.

Wagons -> Train set -> Car segments	8(5 bodies / 6 axles) +1 (twin bodies / 3 axels) 8 x 61,8 + 28,2 = 522m	2 bodies / 4 axles 30,66m x 17 = 521m	2 bodies / 3 axles 26,50m x 20 = 530m	Difference
< 3,55m	cars 270	272 cars- 4 chocks	240 cars	-2
< 3,78m	cars 252	238 cars	240 cars	+12 +5%
< 4,05m	cars 236	238 cars- 4 chocks	240 cars- 4chocks	- 4

< 4,35m	cars 218	204 cars	200 cars	+14 + 7%
< 4,69m	cars 202	204 cars	200 cars	-2
< 5,10m	cars 186	170 cars	160 cars	+16 +9,3%

For a 12 axel wagon carrying 5 swap bodies or 45' containers the impact in term of capacity results from the comparison with the most efficient existing wagons SGGMRSS 90' . The improvement is 4,1% and results in an extra 2 swap bodies more on the train.

For the 12 axel wagon carrying craneable semitrailers the impact in term of capacity is to be compared to the most efficient wagons available on the market. The assumption is to compare the best solution existing today on the market to transport 4m height craneable semitrailers of 27T on pocket wagons and our proposed solution within the maximum length of train authorized: 750m including the Locomotive.

	Number of wagons	Total length of wagons	UNITS	DEAD WEIGHT	Payload	Total Weight
New Proposed solution	10 x 4 w + 1 X 2W + 1 W = 43W	725M	43	10X67,65+34+17,3= 727,8 T	43X27=1 161 T	1888,8 T
T3000 solution	21 X T3000	714m	42	720 T	1134 T	1854 T

This table shows a gain of one semitrailer in length (2.4%) while remaining within the traction capacity of classical powerful electric or diesel locomotive.

8.1.1 Communication equipments impacts

8.1.1.1 General considerations

The problem of the progressive implementation has led operators to choose in the first step a radio connection with the lowest energy consumption with a smart box concentrating all informations fromIoT devices and introducing them in the in-Train network. The basic feature governing the choice after the connecting capacity is the life time of the battery or accumulator with or without the need to have some energy harvester on the wheels or the axels to feed them with energy. The goal is a 6 to 8 years before replacementin order to match the compulsory review of the wagon status for safety reasons.

8.1.1.2 Technical impacts

The main devices interesting wagon owners are

   -- those positioning the wagons by GPS, GSM or less energy consuming solutions like SIGFOX providing much lower accuracy (a few kilometers but algorithms combining the description of the rail network and the results of the mileage device enable to improve the accuracy)

-- those indicating the load on the axels enabling to know when the wagon is running with pay load and when it is empty during a repositioning   -- those indicating the wear and tear of the brake blocks The main devices interesting the RUs are:

   -- those giving the positioning

   -- those detecting the bumps during operations in order to clarify discussions with the shippers

   -- those detecting the pressure at the brake cylinder which needs a specific battery accompanied by devices for the constraints on transmission and for the contact between the shoes and the wheels, these devices being connected with the smart box by IoT technology.

All these impacts do not interfere with the necessity of having a cable communication to have sufficient energy to introduce the Electro pneumatic braking which impact are detailed here under.

8.1.1.3 Financial impact
The benefits derived from the intelligence of the wagon and of the train have to be largely assessed on the basis of expert advice.

The introduction of predictive maintenance:
* for light wagons carrying cars in block trains the controls at each departure of a train in a yard where the operator has a trained staff enables to appreciate the impact of the predictive maintenance to 3 to 4% increase of availability equivalent to 1€ per day per wagon.
* for heavier wagons incorporated in inter-hub trains from yards where the staff has to deal with numerous types of wagons the impact would be estimated at the level of 10% as increase of the availability equivalent to 2,5€ per day per wagon.
* in between block trains of heavier wagons which are not shuttle trains, detector might avoid a part of decision of withdrawal of wagons as the statistics show that on 37 withdrawal only one is really justified and needs an immediate repair. A significant part is due to detect an excess of temperature of the gear box which is decided under the IM responsibility. This part will remain unchanged leaving around 7% of increase of availability equivalent to 2,5€ per day per wagon (rental costs are a bit higher).
* The introduction of sensors enabling the automated brake test:

The operations before the departure from a terminal takes around 30 minutes for two staff for a 750m train of 20 wagons at least. The automated brake test will divide the time by 2 and the number of staff by 2. This generates a benefit of 15 minutes at each and 45 minutes one staff time reduction equivalent to 70€. This represents an economy of 3.5€ per wagon every day to be compared to a rental of 25€ to 35€ per day .
At the same time it increase the availability of the train by 15% for wagon load services down to 6% for shuttle trains running 200 days per year and covering 100000km/year. This would represent a rental economy per wagon per day around 3€ per day.

- The other sensors for the wagon positioning will not generate economies as this service cannot be paid as it is free on the road.
- The wear and tear detectors on the shoes and other types of sensors will enable the predictive maintenance which economies have been described above.
- The introduction of detectors on the cargo temperature may be invoiced to the client and should not interfere in the calculation.

8.1.1.4 Global Financial impact of communication

Taking into account the most frequent cases of wagons in block trains:

- Predictive maintenance 2,5€/day
- Automated brake test   6,5€/day
- Total benefit   9,0€/day

8.1.2 Expert assessment of the impact of the electric line and of the EP brake

The improvement on the maneuverability of the car transportationtrain could allow a gain of 20% on the average commercial speed as those trains would have the capacity to avoid certain stops when there is no possibility to insert a path in between two passenger regional trains in a situation where the freight train would have been obliged to stop involving a significant time to restart. The impact on the asset rotation would be lower as it involves the unloading, loading and preparation of the train for departure from terminals. It could be reduced to 10% according to the distance between terminals. Of course any other operation of marshalling or reshuffling of the train would reduce the impact. However the electric line and EP brakes allow to reduce the preparation time and/or the number of staff deployed for that purpose. This would enable to reach a target of 15% of improvement in asset rotation.

The introduction of the electric line carrying a bus of information enables to install devices allowing the introduction of predictive maintenance. It can be estimated an improvement of the availability of 5% to 10% according to the present maintenance methodology: standard time between technical stops or stops connected to the effective work performed.

The introduction of the electric line may allow to carry on the nearest wagons from the locomotive some reefer containers without installing specific energy production device on the wagons. This market requests a high level of reliability of the availability of the energy as perishables are demanding a very precise temperature control. For frozen food the flexibility may be greater in term of temperature range authorized between -30°C and -20°C giving time to realign the temperature at its maximum.

8.2 Global impact of the capacity improvement and the indications of the experts on the improvements linked to other factors

For the car transportation business

The capacity improvement of each train composed of these new 6-axel/5 bodies wagon can be estimated in average (for various type of cars) at 10%.

The asset rotation would increase by 15% if we take into account a new preparation method and the predictive maintenance an increase of the availability of around 5%. This would globally result in 30% increase capacity.

For the container transportation business
The capacity improvement is 2 more swap bodies on 48 which means around 4% increase. The system would also benefit also of the 15% improvement of asset rotation linked to the new preparation method and to the predictive maintenance. This would result globally in capacity increase of around 20%.

For the 12 axel/4 crane-able semi-trailer wagons   incorporated in the trains The capacity increase would be 2.4%. This system would also benefit from the other improvements quoted here above leading to a global gain of capacity of 17.4%.
All these benefits should be partly reduced because of the consequences of any unexpected break down implying a complex withdrawal of a part of the multi-axel wagon. Despite an introduction of predictive maintenance some breakdowns may happen. For that reason a 5% reduction on these increase seems reasonable on the basis of expert advice.
The other factor inviting to minimize slightly the expected benefits is the existing certain restrictive speed limits when certain parts of the train are empty in case of traffics imbalance. The impact should be minimal as the cases where these constraints would appear are not very frequent.

8.3 Cost evaluation

For this analysis the manufacturer has assumed that the quotation should be based on the industrial cost of such wagons for large series. This is essential to make a comparison with the existing wagons quoted in this analysis.
The basis of the comparison have been defined by NTnetAB in the following table:

	Standard solution	Cost for the standard wagon	New solution	Cost for the new multi axel wagon
Car transportation	2 bodies/3axel wagon:25,60m	113000€	5 bodies/6 axel wagon:61,8m	267000€
Containers transportation	SGGMRSS 90': 29,59m	67500€	5 bodies/12 axel wagon:71,930m	145000€
Crane-able Semi trailer transportation	6 axel pocket wagon:34,2m	117000€	4 bodies/12axel wagon: 67,28m	224000€

On these basis the cost of the various type of trains may be calculated within the length limits previously calculated in order to comply also with the axel loads limits. This will represent the asset costs to which will be applied the gains of efficiency calculated before for each category of traffic.

To fully implement the efficiency increase the equipment of the wagons with EP braking with an overlay solution could be useful on the new designed wagons. The example of the US trains gives an indicative cost of around 6000€ per wagon body and 15000€ per train for the locomotive(after sharingthe cost between 3 sets of wagons) to install the EP braking solution.

8.3.1 Train cost calculation

Applying the basis presented here above the cost of the various train at their optimum capacity is in the following table:

Type of traffic	Standard solution	New design solution	EP brake impact	Total cost of new design solution	Cost variation	Expected efficiency increase
Car transportation	28 W =3,164M€	11Wnew+1S td=3,050M€	0,267M€	3,317M€	4,8%	30%
Containers transportation	24W = 1,632M€	10WN = 1,45M€	without	1,45M€	-12%	4,1%
Crane-able Semi trailer transportation	21W= 2457K€	10WN +1W+1/2 W= 2437K€	without	2437K€	-1%	2,4%

8.3.2 Communication equipments costs

8.3.2.1 The in-wagon costs

The main hardware is the smart box which is a permanent investment to which is to be added the battery renewal and the connection fees. The usual way to calculate the cost is the cost per wagon-day in order to be comparable with the daily rental of the wagon. It represents 0,2€ to 0,5€ per day and it can connect 20 to 25 detectors placed on the wagon. For the sensors and detectors for wear and tear of brake shoes, for measuring the stress in the brake transmission, for detecting the contact with the wheel during the brake test, for detecting temperature in the cargo, for detecting the payload presence or absence the cost is between 0,1€ to 0,3€ per sensor per day. The overall equipment of the wagon with 25 sensors or

detectors and a smart box inclusive of maintenance and connecting fees amount to around 6,25€ per day per wagon.

Specific detectors like the pressure detector for the remote brake test is an investment of 1000€ , like a bump detector is 350€, an energy harvester on bogies is 1200€.

8.3.2.2 The in-train costs

If the transfer of data from the smart box can be done slowly through a train network because the locomotive is equipped to receive it the cost is very low around a few euros per year(1 to 15€/year) per box (included in the daily cost of the smart box described above). If the locomotive is not equipped you will have to add a GSM connection of around (100€ to 200€) per year per smart box.

8.3.2.3 Global costs

For the in-wagon costs installing 20 classical sensors of various types should cost 4€/wagon /day while the smart box will cost 0,5€ per day with a GSM connection added of 0,75€/day. On top of that specific detectors for pressure of the brake cylinder and their battery and energy harvester on the wheels would add another 2€ per day amounting globally with the 3other more elaborated sensors 1€/day and the smart box to 7,25€ per day.

For the locomotive equipment and the GSM or GSMR connection to servers another 1,5 € for 20 wagons in average equivalent to 0,075€/wagon/day should be added raising the global connection costs to 8,35€ per day roughly. In summary:

- Smart box and GSM connection   1,25€/day
- 20 basic sensors   4,0€/day
- 5 Specific sensors and energy harvester 3,0€/day
- Locomotive equipment and GSM/GSMR   0,075€/day
- TOTAL costs   8,35€/day

8.3.3 Conclusion of the cost benefit analysis

The various proposals of new wagon designs are very interesting for the car transportation wagons where the benefits appear very significant for certain categories of car lengths. It is possible to reach around 25% gain in the transportation costs because of the asset rotation, the direct gain in capacity in a given length and a reduction of maintenance. The reduction of the number of axels as long as the stability of the wagon is correct and as long as the speed limit does not appear to be penalizing, induces naturally a reduction of the maintenance cost beyond the simple reduction linked to the possible predictive maintenance.

For the container transportation wagons the cost reduction should reach 16% even without introducing a better train maneuverability. However the gain on the maintenance resulting from the reduction of the number of axels per container carried (2.4 axel/container versus 3/container) should even reduce more the transportation cost.

For the container transportation the proposed solution to have the possibility of a partial flexibility to carry 20′,40′, 45' containers applied to 60' wagons is applicable for 30% of the containers to be 45' without an increase of the train length but with a constraint of working by blocks of 3 wagons not able to be uncoupled operationally because of the absence of the

free rectangle of Bern necessary for the staff safety when decoupling. The increase in capacity in terms of units is limited to 7%. But it is also applicable for 80' wagons on which you can place 2 x 45' containers every group of 3 x 80' wagons not to be uncoupled operationally. On trains of 720m (without the locomotive) you could transport 54 units of which 18 could be 45' units instead of 48 units of which 48 could be 45' units. The gain of efficiency is 12.5%.

For the crane-able semi-trailer transportation trains the new wagon design creates a little efficiency of 3.4% which would not be sufficient for a positive wagon owner decision of investment.

For all types of transport, specifically if uncoupling wagons is not frequent, for instance for shuttle trains, the reduction of time of preparation of the train before departure is a very positive progress. For that purpose equipping the train with an electric line and with an End of Train device enables to perform a brake test from the driver's cabin if sensors have been installed on the wagons. This could be a first step of progress before installing an EP braking system if a progressive implementation plan can be set up.

For the connectivity the cost benefit analysis shows a little profitability of around 7% but this does not include the impacts on the attractiveness of the services offered and the benefit of the better reliability for the infrastructure manager .

9 Business cases analysis

The purpose of this part is to try to analyze 3 flows of traffics of STVA on specific routes trying to detect if progress of efficiency could be introduced rapidly with the innovations that WP22 has proposed and if a viable business case could be set up.

9.1 Definition of the traffics, the routes, the characteristics of the trains studied and their schedules
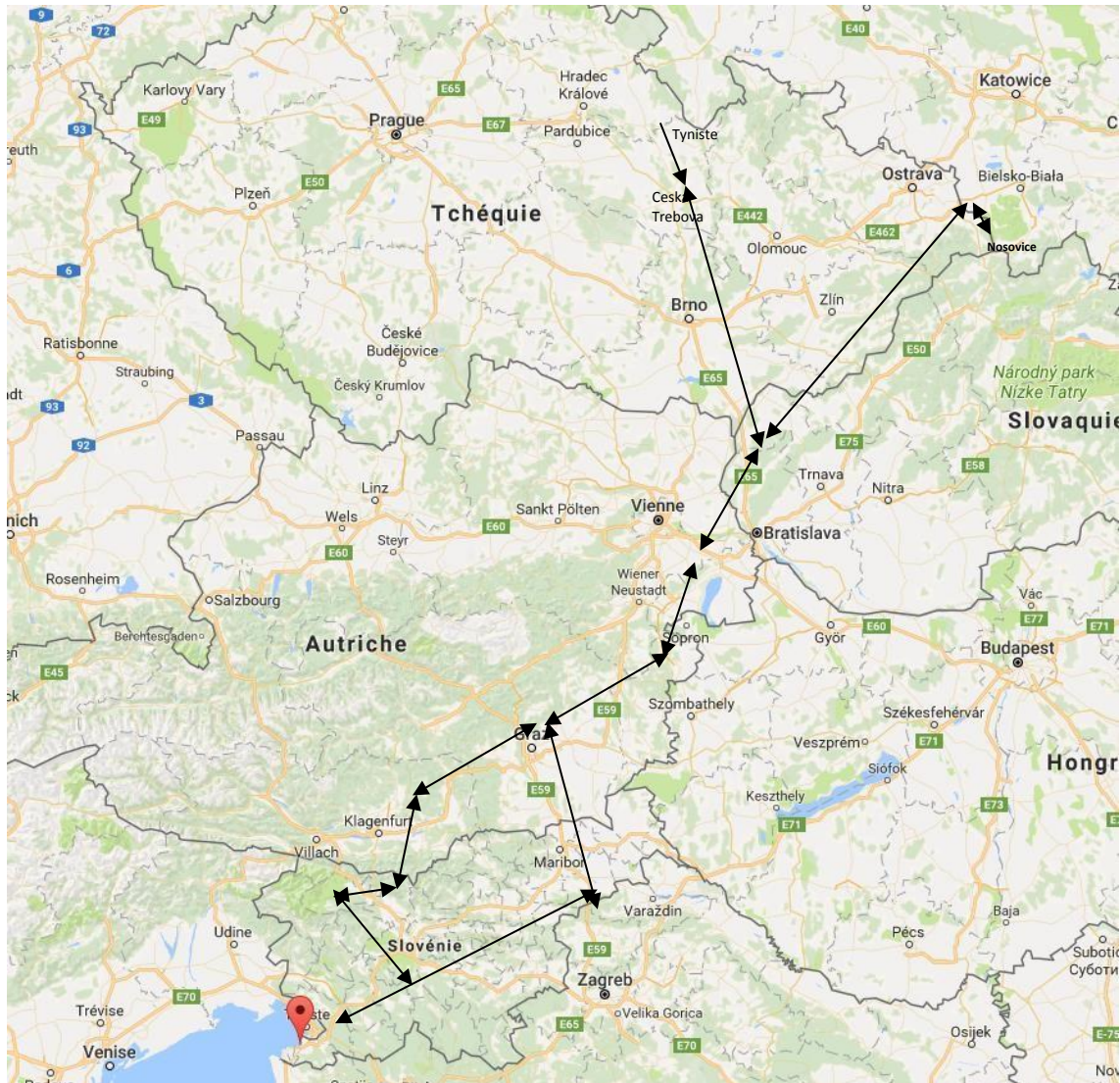
Figure 51: Flows of traffic analyzed. - Source: Newopera for C4R

The flows of traffic proposed by STVA for the study are the following ones:

*   Koper -→CeskaTrebova (Train length 505m)
*   Koper←-→Nosovice (Train length 594m)
*   Tyniste←→ Koper (Train length 505m)

The Characteristics of the trains are given here above.
The basic data is the actual progression of the trains on each route:

Koper to CeskaTrebova

KOPER TOVORNA	2017-06-23T06:02:00.000+02:00	Origine
DIVAČA	2017-06-23T07:33:00.000+02:00	Arrivée
DIVAČA	2017-06-23T07:51:00.000+02:00	Départ
PIVKA	2017-06-23T08:13:00.000+02:00	Passage
POSTOJNA	2017-06-23T08:25:00.000+02:00	Passage
BOROVNICA	2017-06-23T09:05:00.000+02:00	Passage
LJUBLJANA	2017-06-23T09:25:00.000+02:00	Passage
LITIJA	2017-06-23T10:41:00.000+02:00	Passage
ZIDANI MOST	2017-06-23T11:11:00.000+02:00	Passage
CELJE	2017-06-23T11:34:00.000+02:00	Passage
PRAGERSKO	2017-06-23T12:23:00.000+02:00	Passage
MARIBOR	2017-06-23T12:42:00.000+02:00	Arrivée
MARIBOR	2017-06-23T13:42:00.000+02:00	Départ
ŠENTILJ	2017-06-23T14:26:00.000+02:00	Passage
Spielfeld-Straß	2017-06-23T14:32:00.000+02:00	Arrivée
Spielfeld-Straß	2017-06-23T15:02:00.000+02:00	Départ
Leibnitz	2017-06-23T15:12:00.000+02:00	Passage

Graz Hbf (in G)	2017-06-23T15:48:00.000+02:00	Départ
Graz-Fbf (in G)	2017-06-23T15:52:00.000+02:00	Passage
Graz-Vbf (in G)	2017-06-23T15:54:00.000+02:00	Passage
Gratwein-Gratkorn	2017-06-23T16:00:00.000+02:00	Passage
Frohnleiten	2017-06-23T16:13:00.000+02:00	Passage
Bruck a.d.Mur (in Bm)	2017-06-23T16:33:00.000+02:00	Passage
Bruck a.d.Mur-Fbf (in Bm)	2017-06-23T16:35:30.000+02:00	Passage
Kapfenberg	2017-06-23T16:38:30.000+02:00	Passage
Kindberg	2017-06-23T16:50:00.000+02:00	Passage
Mürzzuschlag (in Mz)	2017-06-23T17:22:00.000+02:00	Passage
Mürzzuschlag-Güterbf (in M	2017-06-23T17:25:00.000+02:00	Arrivée
Mürzzuschlag-Güterbf (in M	2017-06-23T17:28:00.000+02:00	Départ
Semmering	2017-06-23T17:40:30.000+02:00	Passage
Payerbach-Reichenau	2017-06-23T18:04:30.000+02:00	Passage
Gloggnitz	2017-06-23T18:12:00.000+02:00	Arrivée
Gloggnitz	2017-06-23T18:28:00.000+02:00	Départ
Neunkirchen N.Ö.	2017-06-23T18:38:30.000+02:00	Passage
Abzww Ne	2017-06-23T18:46:30.000+02:00	Passage
Wiener Neustadt Hbf-Gleis	g2017-06-23T18:48:00.000+02:00	Passage
Wiener Neustadt Hbf (in N	)2017-06-23T18:51:00.000+02:00	Passage
Ebenfurth	2017-06-23T19:08:00.000+02:00	Passage
Wampersdorf	2017-06-23T19:14:00.000+02:00	Arrivée
Wampersdorf	2017-06-23T19:22:00.000+02:00	Départ
Gramatneusiedl	2017-06-23T19:34:30.000+02:00	Passage
Kledering (in Zur)	2017-06-23T19:47:00.000+02:00	Arrivée
Kledering (in Zur)	2017-06-23T19:53:00.000+02:00	Départ
Wien Zvbf (in Zur)	2017-06-23T19:57:00.000+02:00	Passage
Abzww 11821 (in Zur)	2017-06-23T19:58:00.000+02:00	Passage
Wien Zvbf-Einfgr (in Zur)	2017-06-23T20:01:00.000+02:00	Passage
Wien Erdbergerlände (in El	)2017-06-23T20:07:30.000+02:00	Passage
Stadlau Fbf (in St)	2017-06-23T20:14:00.000+02:00	Arrivée
Stadlau Fbf (in St)	2017-06-23T20:18:00.000+02:00	Départ
Wien Süßenbrunn (in Sue)	2017-06-23T20:26:00.000+02:00	Arrivée
Wien Süßenbrunn (in Sue)	2017-06-23T20:34:00.000+02:00	Départ
Deutsch Wagram	2017-06-23T20:41:00.000+02:00	Passage
Strasshof	2017-06-23T20:47:00.000+02:00	Passage
Gänserndorf	2017-06-23T20:54:00.000+02:00	Passage

Angern	2017-06-23T21:02:30.000+02:00	Passage
Dürnkrut	2017-06-23T21:11:00.000+02:00	Passage
Hohenau	2017-06-23T21:22:30.000+02:00	Arrivée
Hohenau	2017-06-23T21:36:00.000+02:00	Départ
Bernhardsthal Fbf	2017-06-23T21:46:00.000+02:00	Passage
Břeclav	2017-06-23T21:53:00.000+02:00	Passage
Břeclav přednádraží	2017-06-23T21:56:00.000+02:00	Arrivée
Břeclav přednádraží	2017-06-23T23:03:00.000+02:00	Départ
Podivín	2017-06-23T23:11:00.000+02:00	Passage
Vranovice	2017-06-23T23:26:30.000+02:00	Passage
Modřice	2017-06-23T23:39:00.000+02:00	Passage
Brno dolní nádraží	2017-06-23T23:43:30.000+02:00	Passage
Brno-Židenice	2017-06-23T23:48:00.000+02:00	Passage
Brno-Maloměřice	2017-06-23T23:52:00.000+02:00	Arrivée
Brno-Maloměřice	2017-06-23T23:57:00.000+02:00	Départ
Brno-Maloměřice stavědl‹	2017-06-23T23:59:30.000+02:00	Passage
Blansko	2017-06-24T00:15:30.000+02:00	Passage
Rájec-Jestřebí	2017-06-24T00:19:30.000+02:00	Passage
Skalice nad Svitavou	2017-06-24T00:26:00.000+02:00	Passage
Svitavy	2017-06-24T00:51:00.000+02:00	Passage
Zádulka odb.	2017-06-24T00:59:00.000+02:00	Passage
Česká Třebová vjezdová sl	2017-06-24T01:05:00.000+02:00	Arrivée au terminus

Koper to Dobra FrydkuMistku

KOPER TOVORNA	2017-06-22T20:33:00.000+02:00	Origine
DIVAČA	2017-06-22T21:51:00.000+02:00	Arrivée
DIVAČA	2017-06-22T22:18:00.000+02:00	Départ
PIVKA	2017-06-22T22:44:00.000+02:00	Passage
POSTOJNA	2017-06-22T22:57:00.000+02:00	Passage
BOROVNICA	2017-06-22T23:38:00.000+02:00	Passage
LJUBLJANA	2017-06-22T23:58:00.000+02:00	Arrivée
LJUBLJANA	2017-06-23T00:25:00.000+02:00	Départ
KRANJ	2017-06-23T00:55:00.000+02:00	Arrivée
KRANJ	2017-06-23T01:03:00.000+02:00	Départ
JESENICE	2017-06-23T02:03:00.000+02:00	Arrivée
JESENICE	2017-06-23T04:05:00.000+02:00	Départ
Rosenbach	2017-06-23T04:36:00.000+02:00	Arrivée
Rosenbach	2017-06-23T04:39:00.000+02:00	Départ
Faak am See	2017-06-23T04:52:00.000+02:00	Passage
Villach Süd Gvbf-Ost (in Vsv)	2017-06-23T04:56:30.000+02:00	Passage
Villach Süd Gvbf-Auen (in Vsv)	2017-06-23T04:58:00.000+02:00	Passage
Villach Westbf (in Vb)	2017-06-23T05:02:00.000+02:00	Arrivée
Villach Westbf (in Vb)	2017-06-23T05:05:00.000+02:00	Départ
Villach Hbf (in Vb)	2017-06-23T05:10:00.000+02:00	Passage
Villach Hbf-Ostbf (in Vb)	2017-06-23T05:12:00.000+02:00	Passage
Föderlach	2017-06-23T05:18:00.000+02:00	Passage
Krumpendorf	2017-06-23T05:34:00.000+02:00	Passage
Klagenfurt Hbf (in Kt)	2017-06-23T05:39:00.000+02:00	Passage
Klagenfurt Ostbf (in Kt)	2017-06-23T05:41:00.000+02:00	Passage
Maria Saal	2017-06-23T05:48:00.000+02:00	Arrivée
Maria Saal	2017-06-23T06:36:00.000+02:00	Départ
St.Veit a.d.Glan (in Vps)	2017-06-23T06:47:00.000+02:00	Passage
Launsdorf-Hochosterwitz	2017-06-23T06:55:00.000+02:00	Passage
Friesach	2017-06-23T07:13:00.000+02:00	Passage

Judenburg	2017-06-23T08:02:00.000+02:00	Passage
Zeltweg	2017-06-23T08:08:00.000+02:00	Passage

Knittelfeld	2017-06-23T08:15:00.000+02:00	Arrivée
Knittelfeld	2017-06-23T08:18:00.000+02:00	Départ
Fentsch-St.Lorenzen	2017-06-23T08:25:00.000+02:00	Passage
Kraubath	2017-06-23T08:31:00.000+02:00	Passage
St.Michael-West (in M)	2017-06-23T08:36:00.000+02:00	Passage
St.Michael-Ost (in M)	2017-06-23T08:38:30.000+02:00	Passage
Leoben Hbf	2017-06-23T08:45:00.000+02:00	Passage
Niklasdorf	2017-06-23T08:49:00.000+02:00	Passage
Bruck a.d.Mur (in Bm)	2017-06-23T08:59:00.000+02:00	Passage
Bruck a.d.Mur-Fbf (in Bm)	2017-06-23T09:01:00.000+02:00	Passage
Kapfenberg	2017-06-23T09:05:00.000+02:00	Arrivée
Kapfenberg	2017-06-23T09:27:00.000+02:00	Départ
Kindberg	2017-06-23T09:40:00.000+02:00	Passage
Mürzzuschlag (in Mz)	2017-06-23T09:59:00.000+02:00	Passage
Mürzzuschlag-Güterbf (in Mz)	2017-06-23T10:02:00.000+02:00	Arrivée
Mürzzuschlag-Güterbf (in Mz)	2017-06-23T10:36:30.000+02:00	Départ
Semmering	2017-06-23T10:50:00.000+02:00	Passage
Payerbach-Reichenau	2017-06-23T11:13:00.000+02:00	Passage
Gloggnitz	2017-06-23T11:21:00.000+02:00	Arrivée
Gloggnitz	2017-06-23T11:31:30.000+02:00	Départ
Neunkirchen N.Ö.	2017-06-23T11:43:00.000+02:00	Passage
Abzww Ne	2017-06-23T11:50:30.000+02:00	Passage
Wiener Neustadt Hbf-Gleisgr 70	2017-06-23T11:51:30.000+02:00	Passage
Wiener Neustadt Hbf (in Nb)	2017-06-23T11:53:30.000+02:00	Passage
Ebenfurth	2017-06-23T12:08:30.000+02:00	Passage
Wampersdorf	2017-06-23T12:15:00.000+02:00	Passage
Gramatneusiedl	2017-06-23T12:30:00.000+02:00	Passage
Kledering (in Zur)	2017-06-23T12:41:00.000+02:00	Arrivée
Kledering (in Zur)	2017-06-23T12:44:00.000+02:00	Départ
Wien Zvbf (in Zur)	2017-06-23T12:47:00.000+02:00	Passage
Abzww 11821 (in Zur)	2017-06-23T12:48:00.000+02:00	Passage
Wien Zvbf-Einfgr (in Zur)	2017-06-23T12:50:00.000+02:00	Passage
Wien Erdbergerlände (in El)	2017-06-23T12:55:00.000+02:00	Passage
Stadlau Fbf (in St)	2017-06-23T13:00:00.000+02:00	Passage
Wien Süßenbrunn (in Sue)	2017-06-23T13:09:30.000+02:00	Passage
Deutsch Wagram	2017-06-23T13:14:30.000+02:00	Passage

Strasshof	2017-06-23T13:18:30.000+02:00	Passage
Gänserndorf	2017-06-23T13:23:30.000+02:00	Passage
Angern	2017-06-23T13:29:30.000+02:00	Passage
Dürnkrut	2017-06-23T13:37:00.000+02:00	Passage
Hohenau	2017-06-23T13:47:30.000+02:00	Arrivée
Hohenau	2017-06-23T14:02:30.000+02:00	Départ
Bernhardsthal Fbf	2017-06-23T14:12:00.000+02:00	Passage
Břeclav	2017-06-23T14:19:00.000+02:00	Passage
Břeclav přednádraží	2017-06-23T14:22:00.000+02:00	Arrivée
Břeclav přednádraží	2017-06-23T16:47:00.000+02:00	Départ
Hodonín	2017-06-23T17:06:00.000+02:00	Passage
Rohatec	2017-06-23T17:11:30.000+02:00	Passage
Moravský Písek	2017-06-23T17:23:00.000+02:00	Passage
Staré Město u Uher. Hradiště	2017-06-23T17:34:00.000+02:00	Passage
Otrokovice	2017-06-23T18:28:00.000+02:00	Passage
Hulín	2017-06-23T18:39:00.000+02:00	Passage
Přerov přednádraží	2017-06-23T18:58:00.000+02:00	Passage
Přerov	2017-06-23T19:00:00.000+02:00	Passage
Prosenice	2017-06-23T19:09:00.000+02:00	Passage
Hranice na Moravě	2017-06-23T19:25:00.000+02:00	Passage
Suchdol nad Odrou	2017-06-23T19:42:00.000+02:00	Passage
Studénka	2017-06-23T19:52:00.000+02:00	Passage
Polanka nad Odrou výh.	2017-06-23T20:04:00.000+02:00	Arrivée
Polanka nad Odrou výh.	2017-06-23T20:28:00.000+02:00	Départ
Odra odb.	2017-06-23T20:32:00.000+02:00	Passage
Ostrava-Vítkovice	2017-06-23T20:36:00.000+02:00	Passage
Ostrava-Kunčice	2017-06-23T20:42:00.000+02:00	Arrivée
Ostrava-Kunčice	2017-06-23T21:31:00.000+02:00	Départ
Vratimov	2017-06-23T21:36:00.000+02:00	Passage
Paskov	2017-06-23T21:41:00.000+02:00	Arrivée
Paskov	2017-06-23T21:48:00.000+02:00	Départ
Lískovec u Frýdku	2017-06-23T21:54:00.000+02:00	Passage
Frýdek-Místek	2017-06-23T21:58:00.000+02:00	Arrivée
Frýdek-Místek	2017-06-23T22:22:00.000+02:00	Départ
Dobrá u Frýdku-Místku	2017-06-23T22:31:00.000+02:00	Arrivée
Dobrá u Frýdku-Místku	2017-06-23T22:31:00.000+02:00	Départ

Tyniste to Koper via CeskaTrebova

Týniště nad Orlicí	2017-06-23T23:42:00.000+02:00	Origine
Borohrádek	2017-06-23T23:50:00.000+02:00	Passage
Choceň	2017-06-24T00:05:00.000+02:00	Arrivée
Choceň	2017-06-24T00:19:00.000+02:00	Départ
Ústí nad Orlicí	2017-06-24T00:33:00.000+02:00	Passage
Parník odb.	2017-06-24T00:38:00.000+02:00	Passage
Česká Třebová odjezdová skupina	2017-06-24T00:45:00.000+02:00	Arrivée
Česká Třebová odjezdová skupina	2017-06-24T01:24:00.000+02:00	Départ
Les odb.	2017-06-24T01:31:00.000+02:00	Passage
Zádulka odb.	2017-06-24T01:33:00.000+02:00	Passage
Svitavy	2017-06-24T01:42:00.000+02:00	Passage
Skalice nad Svitavou	2017-06-24T02:08:00.000+02:00	Passage

Rájec-Jestřebí	2017-06-24T02:14:30.000+02:00	Passage
Blansko	2017-06-24T02:19:00.000+02:00	Passage
Brno-Maloměřice stavědlo 6	2017-06-24T02:34:30.000+02:00	Passage
Brno-Maloměřice	2017-06-24T02:39:00.000+02:00	Arrivée
Brno-Maloměřice	2017-06-24T02:52:00.000+02:00	Départ
Brno-Židenice	2017-06-24T02:55:00.000+02:00	Passage
Brno dolní nádraží	2017-06-24T03:01:00.000+02:00	Passage
Modřice	2017-06-24T03:06:00.000+02:00	Passage
Vranovice	2017-06-24T03:20:00.000+02:00	Passage
Podivín	2017-06-24T03:38:00.000+02:00	Arrivée
Podivín	2017-06-24T03:42:00.000+02:00	Départ
Břeclav přednádraží	2017-06-24T03:52:00.000+02:00	Arrivée
Břeclav přednádraží	2017-06-24T05:38:00.000+02:00	Départ
Břeclav	2017-06-24T05:42:00.000+02:00	Arrivée
Břeclav	2017-06-24T05:42:00.000+02:00	Départ
Bernhardsthal Fbf	2017-06-24T05:49:00.000+02:00	Passage
Hohenau	2017-06-24T05:55:00.000+02:00	Arrivée
Hohenau	2017-06-24T06:34:00.000+02:00	Départ
Dürnkrut	2017-06-24T06:47:00.000+02:00	Passage
Angern	2017-06-24T06:54:30.000+02:00	Passage
Gänserndorf	2017-06-24T07:02:00.000+02:00	Passage
Strasshof	2017-06-24T07:08:30.000+02:00	Passage
Deutsch Wagram	2017-06-24T07:14:30.000+02:00	Passage
Wien Süßenbrunn (in Sue)	2017-06-24T07:19:00.000+02:00	Passage
Stadlau Fbf (in St)	2017-06-24T07:27:00.000+02:00	Passage
Wien Erdbergerlände (in El)	2017-06-24T07:31:30.000+02:00	Passage
Wien Zvbf-Einfgr (in Zur)	2017-06-24T07:36:00.000+02:00	Passage
Abzww 11821 (in Zur)	2017-06-24T07:38:00.000+02:00	Passage
Wien Zvbf (in Zur)	2017-06-24T07:39:00.000+02:00	Arrivée
Wien Zvbf (in Zur)	2017-06-24T07:50:00.000+02:00	Départ
Kledering (in Zur)	2017-06-24T07:54:00.000+02:00	Passage
Gramatneusiedl	2017-06-24T08:05:30.000+02:00	Passage
Wampersdorf	2017-06-24T08:22:00.000+02:00	Passage
Ebenfurth	2017-06-24T08:29:30.000+02:00	Passage
Wiener Neustadt Hbf (in Nb)	2017-06-24T08:42:00.000+02:00	Passage

Wiener Neustadt Hbf-Gleisgr 700 (in N	2017-06-24T08:45:00.000+02:00	Passage
Abzww Ne	2017-06-24T08:46:00.000+02:00	Passage
Neunkirchen N.Ö.	2017-06-24T08:54:00.000+02:00	Passage
Gloggnitz	2017-06-24T09:04:00.000+02:00	Arrivée
Gloggnitz	2017-06-24T09:33:30.000+02:00	Départ
Payerbach-Reichenau	2017-06-24T09:42:30.000+02:00	Passage
Semmering	2017-06-24T10:08:30.000+02:00	Passage
Mürzzuschlag-Güterbf (in Mz)	2017-06-24T10:22:30.000+02:00	Arrivée
Mürzzuschlag-Güterbf (in Mz)	2017-06-24T11:04:00.000+02:00	Départ
Mürzzuschlag (in Mz)	2017-06-24T11:06:30.000+02:00	Passage

Kindberg	2017-06-24T11:25:00.000+02:00	Passage
Kapfenberg	2017-06-24T11:36:00.000+02:00	Arrivée
Kapfenberg	2017-06-24T11:40:00.000+02:00	Départ
Bruck a.d.Mur-Fbf (in Bm)	2017-06-24T11:45:00.000+02:00	Passage
Bruck a.d.Mur (in Bm)	2017-06-24T11:47:00.000+02:00	Passage
Frohnleiten	2017-06-24T12:09:00.000+02:00	Passage
Gratwein-Gratkorn	2017-06-24T12:22:30.000+02:00	Passage
Graz-Vbf (in G)	2017-06-24T12:28:30.000+02:00	Arrivée
Graz-Vbf (in G)	2017-06-24T15:15:00.000+02:00	Départ
Graz-Fbf (in G)	2017-06-24T15:20:00.000+02:00	Passage
Graz Hbf (in G)	2017-06-24T15:23:00.000+02:00	Passage
Kalsdorf (in Kal)	2017-06-24T15:36:00.000+02:00	Passage
Werndorf	2017-06-24T15:40:00.000+02:00	Passage
Leibnitz	2017-06-24T15:54:00.000+02:00	Arrivée
Leibnitz	2017-06-24T15:56:00.000+02:00	Départ
Spielfeld-Straß	2017-06-24T16:08:00.000+02:00	Arrivée
Spielfeld-Straß	2017-06-24T16:28:00.000+02:00	Départ
ŠENTILJ	2017-06-24T16:33:00.000+02:00	Passage
MARIBOR	2017-06-24T16:51:00.000+02:00	Arrivée
MARIBOR	2017-06-24T16:55:00.000+02:00	Départ
PRAGERSKO	2017-06-24T17:15:00.000+02:00	Passage
CELJE	2017-06-24T17:58:00.000+02:00	Passage
ZIDANI MOST	2017-06-24T18:21:00.000+02:00	Passage

LITIJA	2017-06-24T18:52:00.000+02:00	Passage
LJUBLJANA	2017-06-24T19:27:00.000+02:00	Passage
BOROVNICA	2017-06-24T19:47:00.000+02:00	Passage
POSTOJNA	2017-06-24T20:30:00.000+02:00	Passage
PIVKA	2017-06-24T20:42:00.000+02:00	Passage
DIVAČA	2017-06-24T21:04:00.000+02:00	Arrivée
DIVAČA	2017-06-24T21:23:00.000+02:00	Départ
KOPER TOVORNA	2017-06-24T22:49:00.000+02:00	Arrivée au terminus

The routes on which these traffics are operated are mainly belonging to RCF5 (a European Rail Freight corridor).

9.2 The Methodology

9.2.1 The choice of the innovations

The innovations which could be implemented in the short term and which are studied in this document are the following:

- Equipping the wagons with sensors enabling to perform the brake test before departure by the driver alone which results in a gain of half an hour at each departure. For instance on the journey of 19Hours (Koper to CeskaTrebova) this gain represents 2,6% but if we add the loading and unloading time (roughly 5 Hours) the gain is reduced to 2%.

- Equipping the train with an end of train device (EOT) allowing to extend the train length up the 700M gaining in average around 27% from existing maximum length of 505M to 700M with a weight of 760T inbound and 1140T outbound. Existing traction equipment should allow these tonnages as heaviest train hauled from Koper to Divaca which has the most important gradients of 26%o is 1100T inbound.

- Using Road-rail engines for the last mile delivery and maneuvering the wagons to cope with shorter sidings would allow lengthening the trains.

Many other innovations analyzed in WP22 could be proposed but the discussion with STVA has shown that as long as the existing wagon fleet is under-utilized it is not possible to envisage heavy investments like major structural modifications of the wagons or large number of new buildings. These decisions become compulsory only when new rules are to be implemented to keep the wagon compliant with the new regulations or when the fleet becomes commercially obsolete. The business case will be based on light investments deployable in the short term.

The basis of the business case in line with the above considerations will involve sensors for more reliable wagons, a sufficiently accurate positioning to insure a good information for the customer as well as an efficient control of the wagon utilization in the client's premises and a smooth journey on the network. These new sensors will enable to perform the brake test from

the driver's cab. The business case will incorporate not too expensive devices enabling the train lengthening as much as possible on the route of the train. The last mile and the operation of the train on the private sidings will be improved with the use of a road rail engine increasing the competitiveness.

8.2.2 Infrastructure investigation

For each of the routes a precise analysis of the track characteristics has had to be done with the help of the public data included in the RINF. Where public data were not available for an academic study, it has been necessary to check section by section the gradients and the precise length of each crossing loop which is the most fundamental parameter to ensure that such train will be able to cross standard trains and to fully respect the time schedule of all passenger trains.

This analysis has needed a review of all sidings and switches with satellite photos to guarantee the crossing or overtaking possibilities and define what maneuvers may be necessary to perform the crossing safely. This has involved the drawing of the graphics in all sensitive points with the STVA trains and all passenger trains potentially impacted. In particular a specific focus has been made on all single track sections included in the routes used by these flows of traffics. The constraints resulting from the terminal's layout has been studied and operational changes proposals elaborated. In particular the impact of the use of rail-road engines for the last mile delivery and the wagon movements inside terminals has been assessed.

9.2.3 The assumptions in the cost benefit analysis

The costs of the new equipment result from industry partners of WP22 and from contact with suppliers and are based on a large number of equipments to amortize the development costs. Standard traction costs and wagon rental have been used in the calculations. Because of the type of traffics of that business case the trains are quite light and a lengthening of 200m will not change the traction power needed and where double locomotives were necessary the situation will remain unchanged. Because of the EOT the stopping distances will be fully respected despite the lengthening.

The assessment of the costs and benefits will define the needed support policy to achieve the alignment of the various stakeholders interests to obtain a market uptake.

For further developments it would be necessary to have the complete schedule of all trains paths with their characteristics to define the necessary investments on the infrastructure in order to allow any train lengthening to be generalized.

9.2.4 Business cases Feasibility

9.2.4.1 Flows : Koper Tavorna to CeskaTrebova and from Tyniste to Koper Tavorna

9.2.4.1.1 Feasibility on the route through Slovenia

On that route the traffic comes from the port of Koper to the terminals of CeskaTrebova. The trains are today limited to 600T for 505m Towards Ceska and 900T from Tyniste. They have a 19H00 journey to Ceska Trebova and 23 hours journey from Tyniste via Ceska Trebova to Koper. They run on the Route via Divaca, Ljubljana , Maribor , Sentilj through Slovenia, Graz,

Wiena, crossing the border at Breclav to run in Czech Republic. The most sensitive improvement on the route would be the lengthening of the train which has implied a very careful study of paths and crossing loops for overtaking on double track sections or simply crossing on single track sections specifically with lengthened trains to check the feasibility. All passenger trains being positioned on the critical points on the schedule show where difficulties would appear if STVA trains were lengthened in Slovenia. From Koper to Sentilj at the Slovenian Border the two main sensitive zones are the three single track sections between Koper and Divaca, Ljubjana and Jesenice and between Maribor and Sentilj.

The problem on the Koper Divaca connection appears for the crossing of two extended trains which have to use the crossing loop of Kozina instead of Rodik which represents a very minor local deviation of both path schedules (about two to three minutes) without any further impact.

The sensitive section of Maribor to Sentilj has been carefully examined:
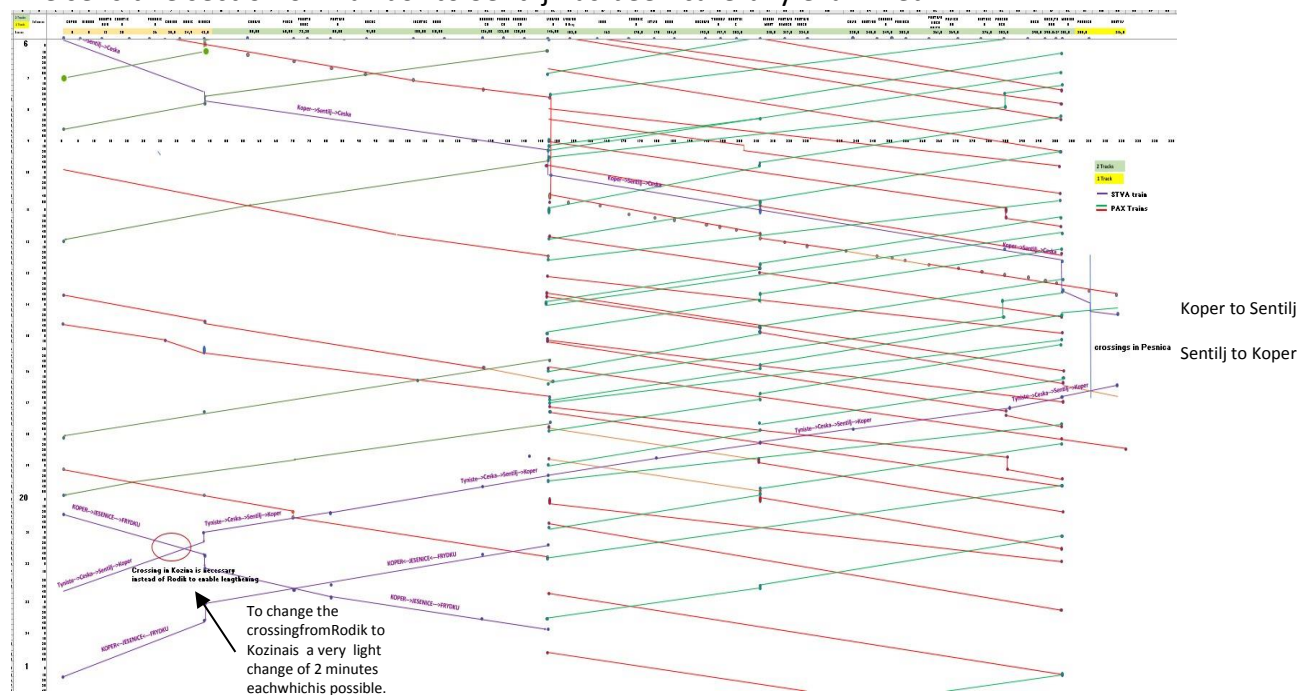
Figure 52: Path Schedules from Koper to Ljubjana for both flows and to Sentilj for Koper to Frydku and from Tyniste. – Source: Newopera for C4R

This examination shows that there is no major problem to extend the train within the limits of the length of the loops as long as the traction capacity is sufficient to respect the previous schedule with an increased load. As the finished car trains are light the weight of the train extended will not create higher risks specifically with the EOT which will increase the safety.
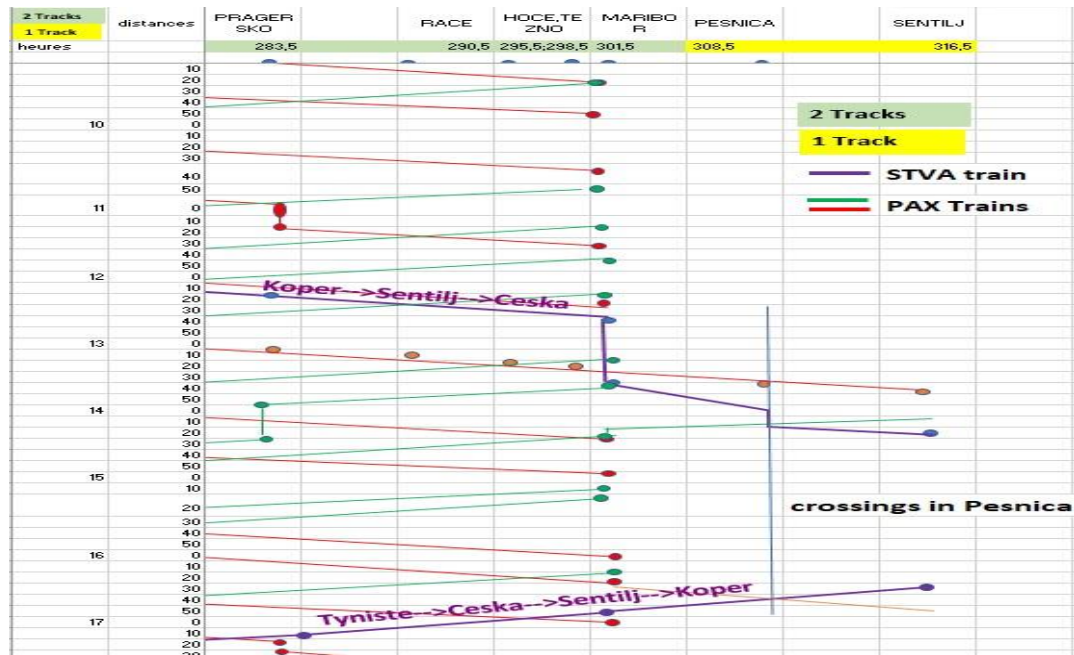
Figure 53: Path Schedule of the critical section from Maribor to Sentilj. – Source: Newopera for C4R

To continue the analysis of the feasibility in Slovenia the section Ljubjana Jenenice has been studied in detail to assess the feasibility.
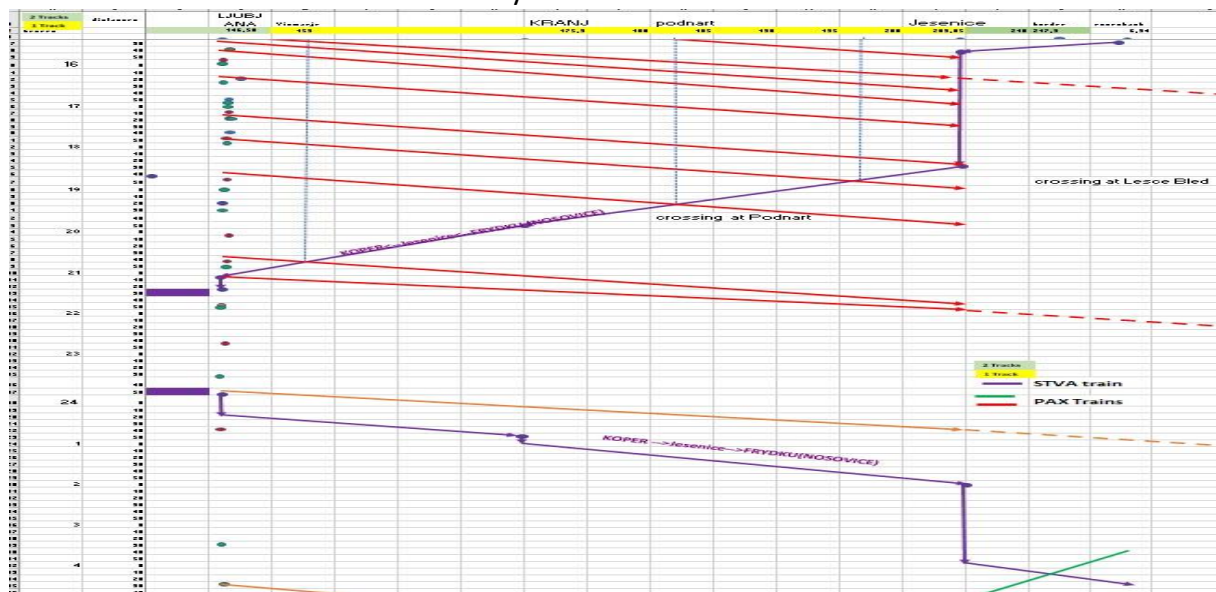
Figure 54: Path Schedule of the critical section from Ljubjana to Jesenice. – Source: Newopera for C4R

In Slovenia the public information on the track characteristics is quite detailed (Annex 1) as regards the infrastructure and enables to confirm that the extended trains will be able to be operated safely with the available traction equipment.

The equipment of the trains with sensors creates a gain at each train departure of half an hour but in the case of the trains studied here there are important buffers and unless this gain would allow a much better path, which is not assessable with the existing data it is impossible to guarantee a specific improvement. However on such trains operated far away from the

base of STVA any unexpected breakdown of a wagon creates important costs to extract the wagon, to unload it , to bring it to a workshop and reload a replacement wagon. So introducing a predictive maintenance may be interesting in such flows and we can consider a gain of 2% on the wagon amortizment costs as it avoids to have 2% wagons ready to replace wagons unable to depart from terminals.

The last element of the feasibility to be studied is the real possibility to load such longer trains at both ends. For that purpose an analysis of the track layout of the terminals and of the departing tracks has to be done. The track layout of the port of Koper is rather complex and the introduction of a remote controlled rail road engine will be very effective.
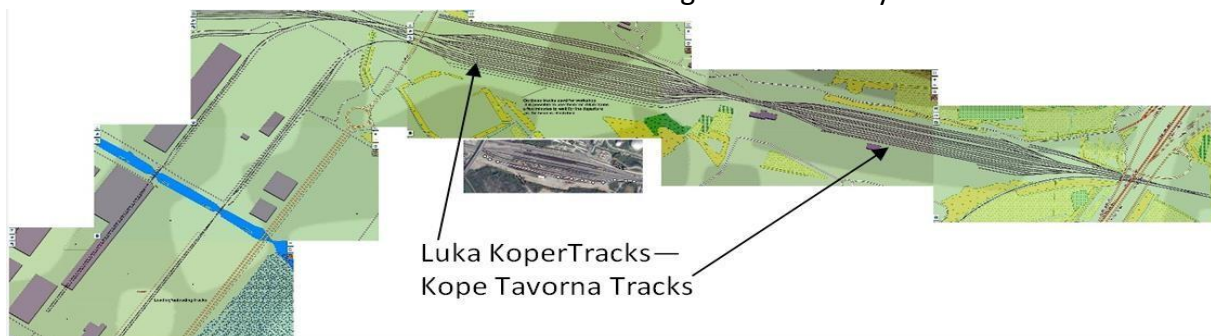
Figure 55: Track layout Port of Koper. – Source: Newopera for C4R

The terminal layout of the port restricts the departure length on the track directly connected to the loading yard to around 550M if the train has to wait on the departure tracks before its effective departure. The only solution is to launch the train directly from the loading area. This is easily feasible with a road rail engine remote controlled by a single agent placed at the front of the train with the road rail engine pushing the train from the tail. This enables to bring the full train in the electrified area of the Koper Luka tracks where it can be connected to the electric locomotive or to the couple of electric locomotive. Then due to the sensors and the EOT equipping the consist the brake test may be done very rapidly and the departure check should have been done one the loading area just before the movement of the train. For an arrival it is even simpler as the main line electric locomotive alone in the outbound direction will stop the train at the entrance of the Koper Luka tracks, decouple from the train which is occupying the whole length of the Koper Tavorna tracks and immediately go back to the Koper Tavorna tracks leaving the place to the rail-road engine which will drag the train to the unloading area having stopped 20m before the end of the track, decouple and on tyre will go to the middle of the train, decouple the rear part of 350m. It will then join the rear end of the train by the other bridge on its tyres, recouple to the end of the train, drag the rear part of the train on 100m roughly to free the switch that gives access to the second loading track, decouple again and joins the end of the arrival train, recouple and drag that second part into its final position.

The only question to be solved is to check if blocking movements at the entrance of the workshop during a relatively short period of Time is acceptable or not. It is to be noted that the departure being at 6H02 and the other at 20h20 the difficulties should be marginal. In Slovenia the feasibility of lengthening the train and of operating 700m trains including traction

should be feasible with a road rail engine for the maneuvers, with a fleet of wagons equipped with sensors and with specific operational procedures to prepare the departure of the train and its arrival.

9.2.4.1.2 Feasability on the route in Austria

The route through Austria is a double track line with 3 sections with a single track line. They are situated between Rosenbach Villach Bahnof and Falk am See and Leibnitz
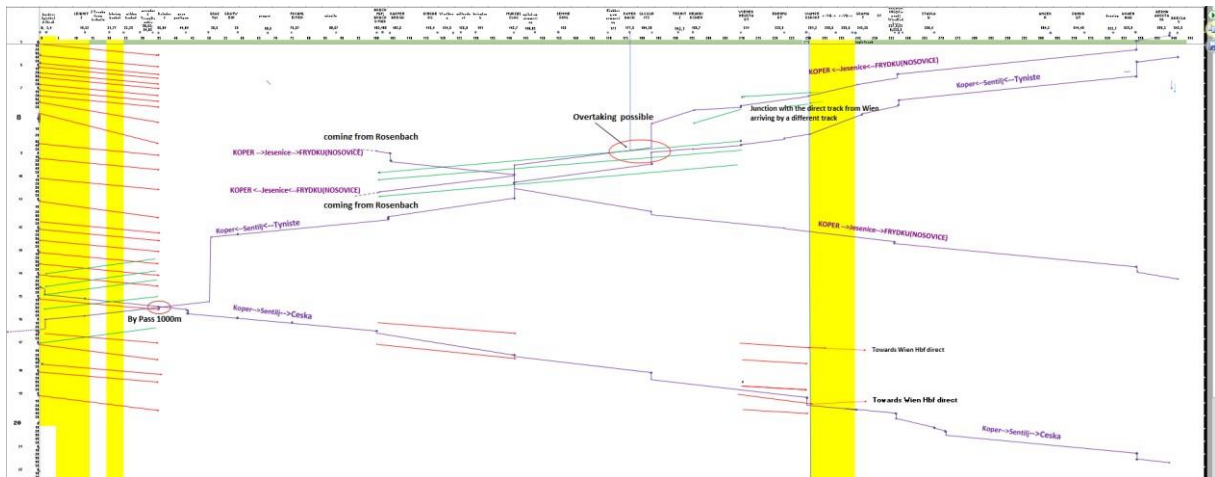
Figure 56: Path schedule through Austria from Sentilj to Breclav involving paths arriving from Jesenice to Breclav. – Source: Newopera for C4R

When entering in Austria the routes from Jesenice are composed of two short section of single track line: from Rosenbach to Leibnitz and from Wildon to Werndorf.
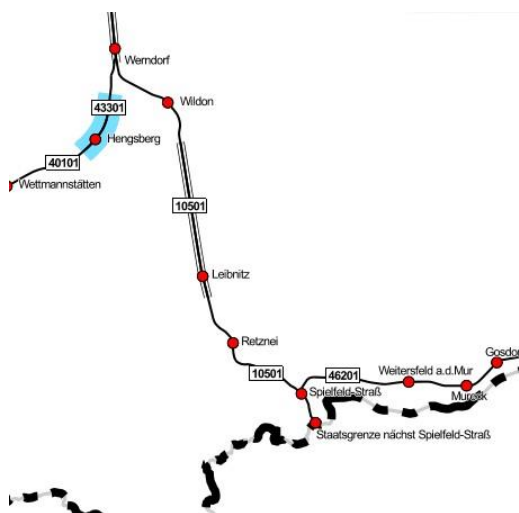
Figure 57: Track line from Rosenbach to Leibnitz and from Wildon to Werndorf. – Source: Newopera for C4R

And from Wampersdorf to Gramateuseidl:

Figure 58: Track line from Wampersdorf to Gramateuseidl. – Source: Newopera for C4R

The path schedule of the trains do not show any difficulty on this route and the crossings or the overtaking will be done safely as most of the loops are longer than 700m . (Annex with all the by-pass length). One of the single track section near Grammateusiedl is even not used by passenger trains according to the published time table but using more direct connections to Wiena. The signaling system will allow 700m as the target is 740m on the rail freight corridors on which are the paths. The path schedule involves significant buffers enabling to give the robustness to the schedule.

The proposed lengthening of the train should not be impossible as the braking distance will be largely respected with the EOT and as the by-pass enable to overtake the train as frequently as necessary if deviations from the path should occur.
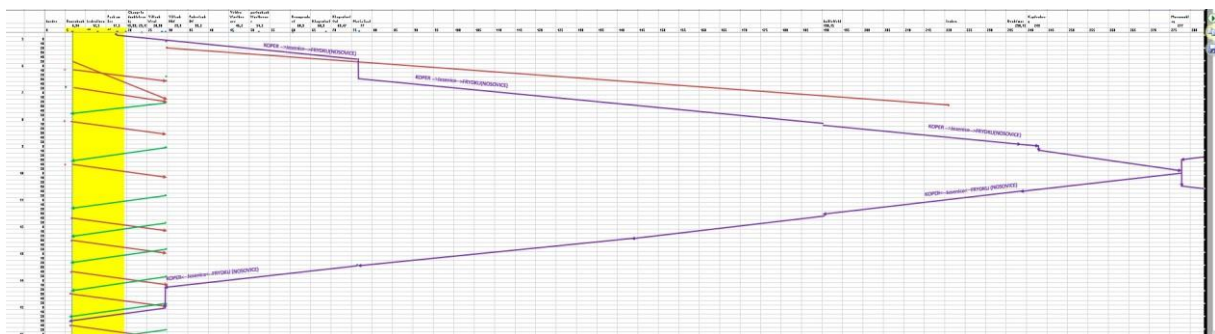
Path from Rosenbach to Murzzuschlag

Figure 59: Path Schedule from Rosenbach to Murzzuschlag. – Source: Newopera for C4R

9.2.4.1.3 Feasibility in Czech Republic

In the Czech Republic the routes are starting from Breclav to Brno, Svitavy, Ceska Trebova Chocen and Tyniste for one flow and From Breclav to Ostrava and Frydku Mitsku for the second flow. Tracks are double track but from Chocen to Tyniste on one flow and from Ostrava Kunice to Frydu-Mitsku and to the Factory.

Certain points of these routes seemed relatively sensitive due to the density of passenger traffics and they have been cautiously investigated to ensure the feasibility of the introduction of the innovative proposals. In these sensitive sections the paths schedule have been drawn on the figures hereunder.
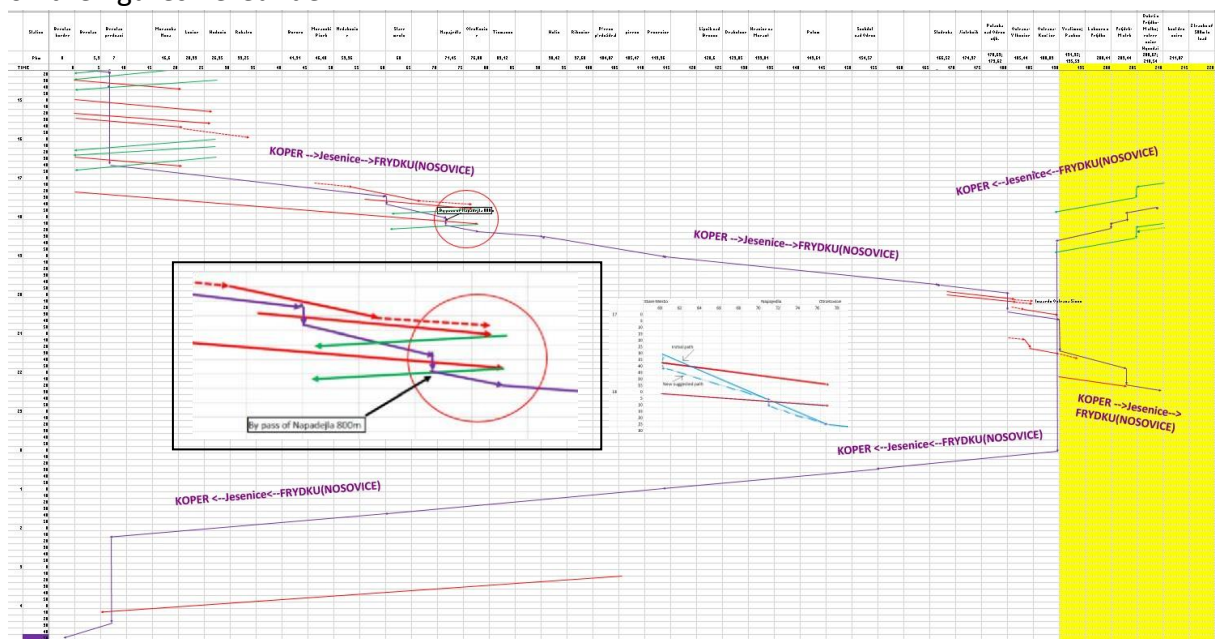
Figure 60: Path Schedule from Breclav to/from Frydu Mitsku (Nosovice). –Source: Newopera for C4R

For these flows of traffic the extension of the length is compatible with the existing crossing loops. On the last run to Dobra u Frydku-Mitsku the use of the Road-Rail engine would enhance the efficiency and allow easy maneuvers inside the factory. This should be easy to allow as it takes place on a single track line on 7 km.

On the terminal itself the track layout allows a road rail engine to place the 700m easily on the loading unloading tracks.

Figure 61: Hyundai factory private siding map. – Source: Newopera for C4R

For the flows to Ceska Trebova and Tyniste the path schedule has also been examined to check the operational feasibility as shown on the figure hereunder.
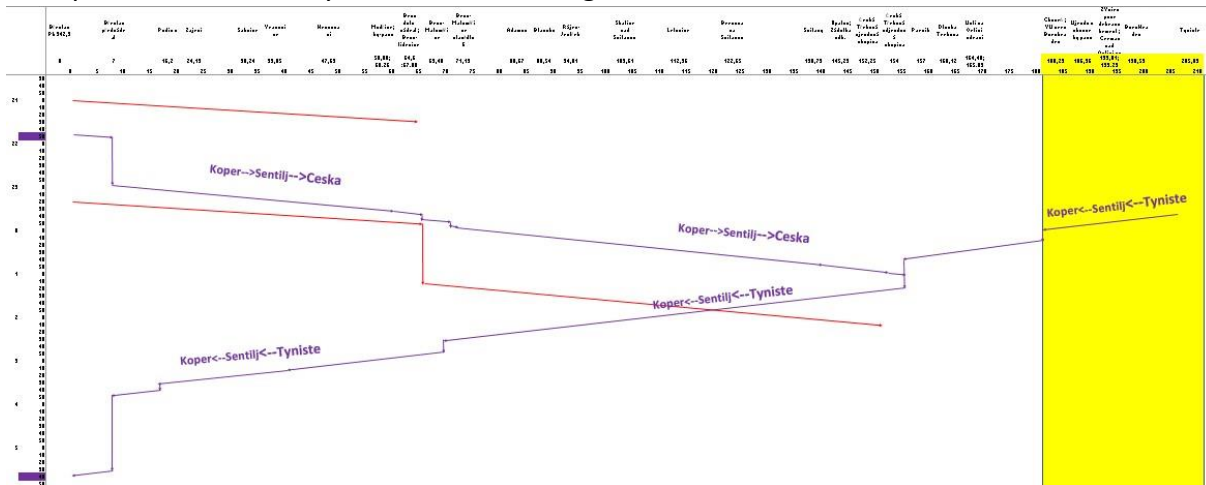
Figure 62: Path Schedule to Ceska Trebova and from Tyniste. – Source: Newopera for C4R

The operations are in fact more complex as Tyniste is the concentration Hub of traffics from Mlada Boleslav and Solnice while the empty wagons return to Ceska Trebova. This part would not change as it is composed of smaller consists of wagons merged to local traffics. The analysis of the flows to Ceska and from Tyniste have not shown any constraints regarding the innovations suggested. However the Breclav sector concentrates all the flows to/from Nosovice, Ceska Trebova and Tyniste. A specific analysis of the movements in the sector has been conducted regarding passenger movements also.

In the analysis it has been assumed that other trains keep their actual length and the check was made that the number of crossing loops or waiting sidings able to accommodate two 700m trains staying simultaneously in Breclav was sufficient.

At the same time analysis of the tracks of Tyniste was done to check if creating a 700m consist was possible and the conclusion was positive as shown on the picture here under.
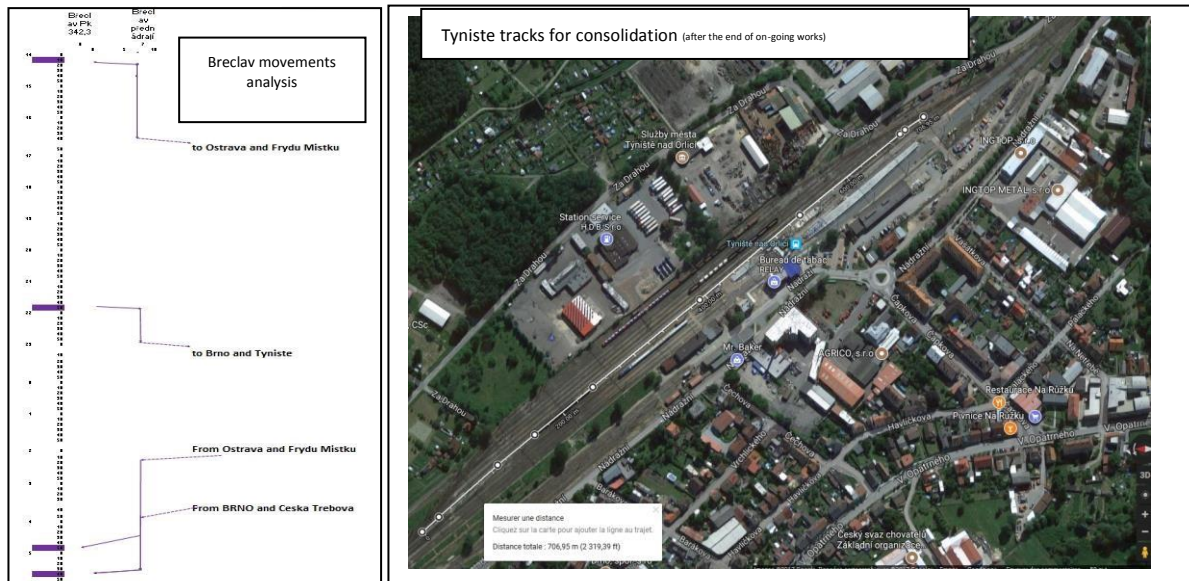
Figure   63: Breclav movement analysis and Tyniste tracks for consolidation satellite view. – Source: Newopera for C4R

To support the feasibility analysis of all routes the list of by-passes and loops with their length is in Annex.

9.3 The cost benefit analysis

9.3.1 The assumptions used for the calculation

9.3.1.1 Costs for the tolls

As these longer trains (100m to 200m more than standard trains according to the networks) will not change the path already attributed as they will have the adequate traction power and the EOT to fully comply with the existing rules no surcharge should be levied unless the actual toll system involves a part linked to the tonnage of the train because of the wear and tear of the rails. This should not be important for the trains studied as finished car trains are relatively light trains (1,2T per meter empty and 1,8T per meter fully loaded). If there is a criteria linked to the length the toll could increase by 20% which with a toll representing in average 11% of the traction cost would mean an increase of 2,2% of the traction cost.

9.3.1.2 Cost of traction

The cost of traction involves the time of disposal of the locomotive which will remain unchanged, the drivers cost which will remain unchanged, the maintenance cost which could marginally increase. The really variable cost is the energy cost as the weight of the train might increase by 16% to 40% if we lengthen a train of 600m to 700m or a train of 500m to 700m. In the precise STVA case the rate is in average 20%. The energy cost generally represents 7% of the traction cost increasing to 10 to 12% for mountainous sections. In our routes the highest point is at 700m above the sea level with 10% of the whole route to be considered as

mountainous. This leads to 7,5% of the traction cost for the traffics studied.The increased weight of the train by 20% will increase the traction cost by 1,5%.

9.3.1.3 Cost of wagons

The cost of the wagon are generally calculated on the number of calendar days of use. They are generally based on a relatively average of kilometer per day when they are used for wagon load activity. In our study the duration of the trip is between 19Hours to 30 hours without including the maneuver times. So it is realistic to take 2 days of use which leads to roughly 12% of the traction cost. So extending the train by 20% in average means that we will add 2,4% of the initial traction cost.

The equipments to be added to the wagon as sensors, detectors, GPS (or equivalents less costly but less precise) find their return on the reliability of the fleet and on the reduction of idle time inside clients premises. They also enable to save staff time and may allow to obtain better paths and thus an operational cost reduction.

For the EOT device which cost is not certain we propose to take the highest value in order to be on the safe side. This represents 4% of the initial traction cost in our case.

9.3.1.4 Cost of the road rail equipment

The characteristics of that equipment is its capability of leaving the rail track at any embedded track area, to move at the speed of a truck when on tyres, to be remote controlled with one hand from 700m easily which means that the train can be driven on sidings by a single man. This equipment has demonstrated its capacity to reduce maneuver costs significantly and specifically to enable to use two embedded tracks by direct traction because of no track need to escape. This equipment will enable easily extending the trains at the loading/unloading points. Its cost should be directly compensated by the reduction of time of shunting locomotives for maneuvers. Its agreement on the National Network is progressing in Germany. So no extra costs should be added for that equipment.

9.3.2 Summary of costs and benefits

By reference to the actual traction cost the various increases are:
- --Traction cost +1,5%
- --Cost of wagons +2,4%
- --Cost of EOT   +4%
- --Cost of the Toll+2,2%

This amounts in Total to 10,1% of the initial traction cost.

At the same time the train capacity increases by 20% which enables to have a new margin of 10% to be shared with the client. Some more other benefits are difficult to assess as the reduction of unexpected breakdowns, in line with the sensor equipment, should reduce unexpected operational costs. The brake test able to be performed from the driver's cab should reduce lost time before departure with a positive impact on staff costs.

9.3.2.1 Risks involved in the analysis

The first risk is linked to the fact that the actual use of the tracks from Koper to Divaca is quite important and that the calculations made in this study imply a real motivation of the

infrastructure manager to collaborate for implementing some derogations to the usual methods of train management.

The second risk is linked to the capacity of the existing locomotives to haul heavier trains without needing a second locomotive. It is however to be noted that the heavier finished car trains are on the outbound flows which take advantage of the gradients down to Koper. It is also to be noted that most of the flows from Koper are heavy flows which do not need long passing tracks enabling to pass by them in most of the stations.

Finally to optimize the use of the line the infrastructure manager of Slovenia has organized the traffic by flights of 4 to 5 freight trains in the same direction. This is favourable to the longer STVA trains if they remain the only ones to be extended as the others are generally limited by their weight on the steep gradients inbound. The actual frequency of the passenger trains between Divaca and Koper 4 to 5 per day in each Direction leaves large periods during which freight trains slots may be placed. The number of trains that could use the line at its optimal capacity in this Divaca Koper section, which is the most critical one on the routes studied, is around 80-90 trains per day from which downtime for maintenance has to be deducted. For these reasons until the new direct line from Koper to Divaca will bebuilt, extending some trains should be considered more favourably as long as the safety criteria can be preserved. The EOT should help in this respect to guaranty the safety level. On the other parts of the itinerary the double tracks are very frequent and the passing tracks sufficiently long.

9.3.3 Conclusion

The cost benefit analysis shows positive and attractive results. The roadmap for an implementation is difficult as long as innovations would be done while the available existing fleet of wagons is not outdated technically and largely amortized without any major increase in maintenance costs. As long as such a situation remains dominant only small investments with a short time to market and a high return on investment will prevail. To go any further voluntary action by the IM or the public authorities have the power to develop an incentive policy to push the stakeholders in the advisable direction.

10 References

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Annexe 1 Sidings or by-pass track

SIDINGS OR BY-PASS TRACKS (in yellow the single tracks are evidenced)

From Koper to Sentilj

By-Pass
700m avec

dérogation

0	KOPER	
5		
12	RIZANA	625m
20	HRASTOVLJE	600m
	CRNOTICE	650m
26		
30,5		
34,9	PRESNICA	
42,5	KOZINA	800m
	RODIK	653m
DIVACA	>800m	
55,50		
	GORNJE	
68,50	PIVKA	250m
73,30	PRESTRANEK	621m
80,50	POSTOJNA	>700m
91,50		700m
	RAKEK	
105,50	LOGATEC	900m
115,00	VERD	860m
126,00	BOROVNICA	660m
132,50	PRESERGE	900m
138,50	BREZOVICA	760m
146,50	LJUBJANA	700m
152,5	LJUBJANA Zalog	>700m
162	LAZE	900M
170,5	KRESNICE	750m
178	LITIJA	900m

184,5	SAVA	900m
193,5	ZAGORJE	0m
197,9	TRBOVLJE	700m
202,8	HRASTNIK	300m
210,5	ZIDANI MOST	700m
217,5	POSTAJA RIMSKE	930m
224,5	POSTAJA LASKO	700M
235,5	CELJE	700m
245,5	SENTJUR	900m
249,5	GROBELNO	
253,5	PONIVKA	700m
	POSTAJALISCE	
261,5	DOLGA GORA	
269,5	POLJICANE	>1000m
276,5	BISTRICA	700M
283,5	PRAGERSKO	900m
290,5	RACE	600m
295,5	HOCE	600m
298,5	TEZNO	
301,5	MARIBOR	

308,5	PESNICA	700m
316,5	SENTILJ	650m

From Ljubjana to Jesenice

By Pass

0	Ljubljana	1000m
1,412	voies	600m
4,4	Ljubjana Stegne	
6,35	Ljubljana Vizmarje	900m
12,51	Medvode	1200m
16,42	Retece station	
19,42	skofja loka	800m
28,94	Kranj	700m
39,88	podnart	800m
51,12	lesce bled	750m
56,12	zirovnica	540m
61,12	slovenska jarovnik	400m
63,98	jesenice	1000m
71,05	Border of Austria	

From Border of Austria to Bruk/Mur

0	Border Jesenice	
6,34	Rosenbach	700m
12,5	Ledenitzen	700m
17,5	Faak am See	700m
19,93	Change to double track	
23,15	Godersdorf	400m
28,38	Villach West	800m
29,9	Villach Hbf	800m
39,2	Foderlach Bf	700m
46,2	Velden Worther see	700m
54,5	portschach Worthersee	800m
60,9	Krumpendorf	700m
68,3	Klagenfurt	1000m
69,47	Klagenfurt Ost	600m/700m
77	Maria Saal	700m
87,8	St Veit	700m
96,78	Launsdorf	1000m
110,2	treibach	700 m

121,08	Freisach	800m
142,5	Mariahoft St Lambrech	700m
150,79	Schieffling	800m
157,55	Unzmarkt Bf	>700m
169,95	Talheim-pos Bf	700m
176	Judenburg	800m
183,84	Zeltweg	>800m
191,5	Knittfeld	>700m
197,83	Fentsch	>700m
206,24	Kraubat	900 m
212,76	St Michael west	
213,5	St Michael ost	No By pass
221,65	Leoben	700m
227	Niklasdorf	800m
238,15	Bruck a.d MurHbf	

From Border Sentilj to berder of Czech Republic Breclav

		By-pass
0	border at Sentilj	
2,4	Spielfeld-Straß	900m
13,52	LEIBNITZ	000m
21,77	2 Tracks from Leibnitz lebring banhof	2 tracks
25,29	wildon banhof	700m
30,62	werndorf	1000m
34,02	TransDanubia	700m
36,04	Kalsdorf	000m
44,04	graz puntigam	700m
59	GRATWEIN	900m
68,6	peggau	000m
76,67	FROHNLEITEN	000m
88,67	mixnitz	600m
102	BRUCK D MUR	700m
103	BRUCK FBF	700m
105,6	KAPFENBERGH	800m
119,4	KINDBERG	500m
124,3	Wartberg	700m
126,8	mitterdorf	000m
131	krieglach	700m
142,7	MURZUSCLAG	700m
148,85	spital am semmering	700m
156	SEMMERING	700m
171	Eichberg am semmering	0m
177,3	PAYERBACH	700m
184,28	GLOGGNITZ	500m
192,05	TERNITZ	000m

196,7	NEUNKIRCHEN	000m	
211	WIENER NEUSTADT	000m	
223,9	EBENFURT	900m	
231,2	WAMPERSDORF	700m	
239,6	By-Pass	800m	
245,26	GRAMAT	1000m	
257,3	KLEDERING	800m	
258	WIEN ZVF	800m	
259,9	WIEN ERDBERG		
268,4	STADLAU	700m	
304,2	ANGERN	800m	
314,43	DUNKRUT	200m	
322,7	drosing	800m	
329,3	HOHENHAU	800m	
339,5	BERNHARDSTAHL		0
342,3	BRECLAV	border	
	Breclav HBf	1000m	

From Breclav to Tyniste

	Bernhardsthal Fbf	
0	Břeclav Pk 342,3	
7	Břeclav přednádraží	
	Břeclav přednádraží	>700m
16,2	Podivín	
24,19	Zajeci	800m
30,24	Sakvice	800m
39,85	Vranovice	800m
47,69	Hrusovani	900m
58,88	Modřice	800m
60,26	by-pass	800m
64,6	Brno dolní nádraží	800m
67,88	Brno-Židenice	700m
69,48	Brno-Maloměřice	>1000m
	Brno-Maloměřice	>800m
71,13	Brno-Maloměřice stavědlo 6	
80,67	Adamov	no by pass
88,54	Blansko	700m
94,81	Rájec-Jestřebí	700m
103,61	Skalice nad Svitavou	1000m
112,96	Letovice	700m
122,65	Bresova na Svitavou	700m
138,79	Svitavy	700m
145,23	0patov	700m
	Zádulka odb.	700m

152,25	Česká Třebová vjezdová skupina		
154	Česká Třebová odjezdová skupina		
157	Parnik		
160,12	Dlouha Trebova	2000m	
164,48	Usti na Orlici	700m	
165,83	Usti na Orlici ndrazi	no	by pass
180,29	Choceň	700m	
	VU vers Borohradec	700m	
186,36	Ujezdo u chocne by pass		
193,01	2Voies pour debranchement	600m	
193,29	Cerman nad Orlici en VU		
198,53	BoroHradec	600m	
205,83	Tyniste	700m	

From Breclav to Nosovice

0	Breclav border	
5,3	Breclav	>700m
7	Breclav prednazi	700m
16,6	Moravska Nova	700m
20,93	Luzice	1000m
26,35	Hodonin	1000m
33,25	Rohatec	1000m
41,31	Bzenec	900m
46,48	Moravski Pisek	1000m
53,96	Nedakonice	1000m
60	Stare mesto	1800m
71,45	Napajedla	850m
76,88	OtroKovice	1000m
83,12	Tiumacov	780m
90,42	Hulin	1000m
97,68	Rikovice	1000m
104,07	Přerov přednádraží	1000m
105,47	pierov	800m
113,36	Prosenice	1200m
120,6	Lipnik nad Becvou	900m
129,05	Drahotuse	1000m
133,81	Hranice na Moravě	1000m
143,61	Polom	800m
154,57	Suchdol nad Odrou	1000m
166,52	Studenka	1000m
174,37	Jistebnik	700m
178,69	Polanka nad Odrou výh.	
179,62	Polanka nad Odrou výh.	1000m
185,44	Ostrava-Vítkovice	800m
188,89	Ostrava-Kunčice	1000m

191,32	Vratimov	
195,59	Paskov	1000m
200,41	Lískovec u Frýdku	700m
203,44	Frýdek-Místek	700m
208,67	Dobrá u Frýdku-Místku	400m X 2
210,54	entree usine Hyundai	
211,87	bout des voies	
	2 tracks of 500m to load	

Annexe 2 Characteristics of Slovenian tracks utilized by the flows

LINE SECTION	INTERNATIONAL DESIGNATION OF THE LINE	NUMBER OF TRACKS	DESIGNATION OF KM		DISTANCE BETWEEN SECTIONS	BRAKING DISTANCE IN METERS	SIGNALLING EQUIPMENT	TELECOMMUNI – CATION SYSTEMS	TRACTION SYSTEMS	AXLE LOAD	AVAILABILITY OF PIGGY-BACK SYSTEM "A"	AVAILABILITY OF RADIO DISPATCH CONNECTIONS	LINE CAPACITY	
			FROM	TO									UTILIZED CAPACITY OF TRAIN (IN 24 HOURS)	UTILIZED CAPACITY OF LINE (%)
1	2	3	4a	4b	5	6	7	8	9	10	11	12	13	14
MAIN LINE 10 d.m. – DOBOVA – LJUBLJANA														
d.m. - Dobova	E 70 X. corridor RFC 6	2	451,2	453,3	2,1	1000	MO	digital	25 kV	D 3	yes	yes	286	23
Dobova - Brežice		2	453,3	459,1	5,8	1000	APB	digital	3 kV	D 3	yes	yes		
Brežice - Krško		2	459,1	467,6	8,5	1000	APB	digital	3 kV	D 3	yes	yes		
Krško - Brestanica		2	467,6	471,8	4,2	1000	APB	digital	3 kV	D 3	yes	yes		
Brestanica - Blanca		2	471,8	477,7	5,9	1000	APB	digital	3 kV	D 3	yes	yes		
Blanca - Sevnica		2	477,7	485,7	8,0	1000	APB	digital	3 kV	D 3	yes	yes		
Sevnica - Breg		2	485,7	494,3	8,6	1000	APB	digital	3 kV	D 3	yes	yes	345	21
Breg - Zidani Most		2	494,3	502,1	7,7	1000	APB	digital	3 kV	D 3	yes	yes		
Zidani Most - Hrastnik	E 69 E 70 V. corridor X. corridor RFC 5 RFC 6	2	502,1	509,8	7,8	1000	APB	digital	3 kV	D 3	yes	yes	300	51
Hrastnik - Trbovlje		2	509,8	514,6	4,8	1000	APB	digital	3 kV	D 3	yes	yes		
Trbovlje – Zagorje		2	514,6	519,1	4,5	1000	APB	digital	3 kV	D 3	yes	yes		
Zagorje - Sava		2	519,1	527,8	8,7	1000	APB	digital	3 kV	*	yes	yes		

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TECHNICAL DATA ON RAIL LINES														
1	2	3	4a	4b	5	6	7	8	9	10	11	12	13	14
Sava – Litija	E 69 E 70 V. corridor X. corridor RFC 5 RFC 6	2	527,8	534,6	6,8	1000	APB	digital	3 kV	*	yes	yes	300	51
Litija - Kresnice		2	534,6	541,9	7,3	1000	APB	digital	3 kV	D 3	yes	yes		
Kresnice - Laze		2	541,9	551,0	9,1	1000	APB	digital	3 kV	D 3	yes	yes		
Laze - Ljubljana Zalog		2	551,0	557,8	6,8	1000	APB	digital	3 kV	D 3	yes	yes		
Ljubljana Zalog - Ljubljana		2	557,8	565,9	8,1	1000	APB, OP	digital	3 kV	D 3	yes	yes		

*   left track D 3, right track D 4

LINE SECTION	INTERNATIONAL DESIGNATION OF THE LINE	NUMBER OF TRACKS	DESIGNATION OF KM		DISTANCE BETWEEN SECTIONS	BRAKING DISTANCE IN METERS	SIGNALLING EQUIPMENT	TELECOMMUNI-CATION SYSTEMS	TRACTION SYSTEMS	AXLE LOAD	AVAILABILITY OF PIGGY-BACK SYSTEM "A"	AVAILABILITY OF RADIO DISPATCH CONNECTIONS	LINE CAPACITY	
			FROM	TO									UTILIZED CAPACITY OF TRAIN (IN 24 HOURS)	UTILIZED CAPACITY OF LINE (%)
1	2	3	4a	4b	5	6	7	8	9	10	11	12	13	14
MAIN LINE 20 LJUBLJANA – JESENICE – d.m.														
Ljubljana - Ljubljana Šiška	E 65 X. corridor	1	566,4	567,3	0,9	1000	APB, OP	digital	3 kV	D 3	yes	yes	118	74
Ljubljana Šiška - Ljubljana Vižmarje		1	567,3	572,1	4,8	1000	APB	digital	3 kV	D 3	yes	yes		
Lj. Vižmarje - Medvode		1	572,1	578,2	6,1	1000	APB, DVP	digital	3 kV	D 3	yes	yes		
Medvode – Škofja Loka		1	578,2	585,7	7,5	1000	APB, DVP	digital	3 kV	D 3	yes	yes		
Škofja Loka – Kranj		1	585,7	594,5	8,8	1000	APB, DVP	digital	3 kV	D 3	yes	yes		
Kranj – Podnart		1	594,5	605,3	10,8	1000	APB, DVP	digital	3 kV	D 3	yes	yes	85	91
Podnart - Lesce Bled		1	605,3	617,3	12,0	1000	APB, DVP	digital	3 kV	D 3	yes	yes		
Lesce Bled - Žirovnica		1	617,3	622,3	5,0	1000	APB, DVP	digital	3 kV	D 3	yes	yes		
Žirovnica - Slovenski Javornik		1	622,3	627,4	5,1	1000	APB, DVP	digital	3 kV	D 3	yes	yes		
Slovenski Javornik - Jesenice		1	627,4	630,2	2,8	1000	APB, DVP	digital	3 kV	D 3	yes	yes		
Jesenice – Jesenice d.m.		2	630,2	637,3	7,1	1000	MO, OP	digital	15 kV	D 3	yes	yes		40
1	2	3	4a	4b	5	6	7	8	9	10	11	12	13	14
MAIN LINE 30 ZIDANI MOST – ŠENTILJ – d.m.														
Zidani Most – Rimske Toplice	look next page	2	502,1	509,6	7,6	1000	APB	digital	3 kV	C 3	yes	yes	348	35
Rimske Toplice - Laško		2	509,6	516,6	7,0	1000	APB	digital	3 kV	C 3	yes	yes		
Laško - Celje		2	516,6	527,0	10,3	1000	APB	digital	3 kV	C 3	yes	yes		
Celje - Šentjur	E 67 E 69 V. corridor X. corridor RFC 5 RFC 6	2	527,0	537,6	10,7	1000	APB	digital	3 kV	D 4	yes	yes	319	44
Šentjur – Grobelno		2	537,6	541,1	3,5	1000	MO, OP	digital	3 kV	D 4	yes	yes		
Grobelno - Ponikva		2	541,1	545,3	4,2	1000	MO	digital	3 kV	D 4	yes	yes	170	69
Ponikva - Poljčane		2	545,3	561,2	15,9	1000	MO	digital	3 kV	D 4	yes	yes		
Poljčane - Slovenska Bistrica		2	561,2	568,8	7,6	1000	MO	digital	3 kV	C 3	yes	yes	214	58
Slovenska Bistrica - Pragersko		2	568,8	575,2	6,4	1000	MO	digital	3 kV	C 3	yes	yes		
Pragersko - Rače	E 67 X. corridor RFC 5	2	575,2	581,6	6,5	1000	MO	digital	3 kV	D 4	yes	yes	246	57
Rače - Hoče		2	581,6	586,9	5,2	1000	MO	digital	3 kV	D 4	yes	yes		
Hoče - Maribor Tezno		2	586,9	590,8	3,9	1000	MO	digital	3 kV	D 4	yes	yes		
Maribor Tezno - Maribor		2	590,8	594,0	3,1	1000	MO, OP	digital	3 kV	C 3	yes	yes		
Maribor - Pesnica		1	594,0	600,3	6,4	1000	MO	digital	3 kV	C 3	yes	yes	67	82
Pesnica – Šentilj		1	600,3	608,0	7,7	1000	MO	digital	3 kV	C 3	yes	yes		
Šentilj - d.m.		1	608,0	610,4	2,4	1000	MO	digital	3 kV	C 3	yes	yes		
MAIN LINE 50 LJUBLJANA – SEŽANA – d.m.														
Ljubljana – Brezovica	E 65 E 69 E 70 V. corridor RFC 5 RFC 6	2	565,9	573,8	7,9	1000	DVP, MO, OP	digital	3 kV	D 3	yes	yes	207	67
Brezovica - Preserje		2	573,8	580,6	6,8	1000	DVP, MO, OP	digital	3 kV	D 3	yes	yes		
Preserje - Borovnica		2	580,6	586,6	7,1	1000	DVP, MO, OP	digital	3 kV	D 3	yes	yes		
Borovnica - Verd		2	586,6	597,8	10,1	1000	DVP, MO, OP	digital	3 kV	D 3	yes	yes	153	83
Verd – Logatec		2	597,8	607,1	9,3	1000	DVP, MO, OP	digital	3 kV	D 3	yes	yes		
Logatec - Rakek		2	607,1	621,2	14,1	1000	DVP, APB, OP	digital	3 kV	D 3	yes	yes		
Rakek – Postojna		2	621,2	632,8	11,6	1000	DVP, MO, OP	digital	3 kV	D 3	yes	yes		
Postojna - Prestranek		2	632,8	639,3	6,5	1000	DVP, MO, OP	digital	3 kV	D 4	yes	yes	259	50
Prestranek – Pivka (excluding)		2	639,3	643,9	4,6	1000	DVP, MO, OP	digital	3 kV	D 3	yes	yes		
Pivka		2	643,9	647,1	3,2	700	DVP, MO, OP	digital	3 kV	D 3	yes	yes		
Pivka (excluding) – Gornje Ležeče		2	647,1	657,5	10,4	1000	DVP, MO, OP	digital	3 kV	D 3	yes	yes	151	78
Gornje Ležeče – Divača		2	657,5	669,6	12,1	1000	DVP, MO, OP	digital	3 kV	D 4	yes	yes		
Divača – Sežana	E 70 V. corridor RFC 5, 6	2	669,6	679,2	9,6	1000	DVP, MO, OP	digital	3 kV	D 3	no	yes	205	32
Sežana – Sežana d.m.		2	679,2	682,5	3,3	1000	MO	digital	3 kV	D 3	no	yes		16

MAIN LINE 60 DIVAČA – branching PREŠNICA														
Divača - Rodik	E 69 V. corridor RFC 5, 6	1	0,0	7,4	7,4	1000	DVP, APB	digital	3 kV	D 3	yes	yes		
Rodik - Kozina		1	7,4	11,8	4,4	1000	DVP, APB	digital	3 kV	D 3	yes	yes	90	98
Kozina – branching Prešnica		1	11,8	16,5	4,7	1000	DVP, APB	digital	3 kV	D 3	yes	yes		

MAIN LINE 62 branching PREŠNICA – KOPER														
branching Prešnica – Črnotiče	E 69 V. corridor RFC 5 RFC 6	1	0,0	5,5	5,5	1000	DVP, APB	digital	3 kV	D 3	yes	yes		
Črnotiče - Hrastovlje		1	5,5	14,4	8,9	1000	DVP, APB	digital	3 kV	D 3	yes	yes		
Hrastovlje - Rižana		1	14,4	21,4	7,0	1000	DVP, APB	digital	3 kV	D 3	yes	yes	90	98
Rižana - Koper tovorna		1	21,4	29,0	7,6	1000	DVP, APB	digital	3 kV	D 3	yes	yes		
Koper tovorna - Koper		1	29,0	31,5	2,5	1000	DVP, MO	digital	3 kV	D 3	yes	yes		