C4R

Capacity for Rail

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

Design requirements and improved guidelines for design (track loading, resilience & RAMS)

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EXECUTIVE SUMMARY

This report is the first deliverable for Work Package 1.1 under Sub-Project1 (SP1) of the Capacity4Rail (C4R) project.

The aim of this deliverable is to identify the design requirements to develop new track concepts that address the general objectives of the project, i.e. an affordable, adaptable, automated, resilient and high capacity railway infrastructure.

Those requirements comprise geometrical, mechanical, environmental, construction, maintenance, operational and safety features that the new track system should accomplish. When possible, the requirements have been differentiated between high-speed and mixed traffic, that are the two scenarios set out in the Description of Work.

The starting point for the developments are the current track systems, that are broadly described in this report, and the regulatory framework, in particular the Technical Specifications for Interoperability (TSI). This will ensure that the new systems are competitive against existing track concepts and will ease the homologation and market implementation in every Member State.

In order to feed the design with cutting-the-edge knowledge on railway infrastructure, three guidelines have been drafted: 1) Deeper knowledge on track actual loads; 2) Resilience to natural events; 3) Combined design to cost and RAMS methodologies. These reports, annexes to the deliverable, are able to be used by designers as stand-alone documents.

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ABBREVIATIONS AND ACRONYMS

Abbreviation / Acronym	Description
C4R	Capacity4Rail
DoW	Description of Work
EN	European Standard
HBL	Hydraulically Bounded Layer
HS(L)	High Speed (Line)
LCC	Life Cycle Cost
RAMS	Reliability, Availability, Maintainability and Safety
S&C	Switches and Crossings
SP	Sub-Project
TEN	Trans-European transport Network
TSI	Technical Specifications for Interoperability
UIC	Union Internationale des Chemins de Fer
WP	Work Package

1 INTRODUCTION

One of the very first tasks of C4R is to define a comprehensive roadmap to describe the necessary steps to develop and implement innovation and to progress from the current state-of-the-art to a shared global vision of the 2050 railway along realistic scenarios.

Five major requirements have been defined for all the developments within this project: The future railway system should be affordable, adaptable, automated, resilient and high capacity.

From its first utilisation in the sixteenth century, railway infrastructure has been a reference of capacity, speed, reliability and environmentally friendly for all terrestrial transport modes. The track concepts have evolve since then, although the basic premises remain the same: two rails as supporting and guiding elements on top of resistant structures. Furthermore, during the last 50 years new materials and technologies have been introduced within this inertial, resistant to changes transport mode, but only after long periods of developing and testing in real operational environments.

Recent research projects have increased considerably the knowledge on track infrastructure. Large amounts of data from extensive monitoring, powerful numerical methods and accumulated experience from infrastructure managers have been successfully used to identify and understand the strengths and weaknesses of different track systems.

The aim of this first task T1.1.1 on Work Package 1 is to collect this state-of-the-art knowledge and set the basis for the generation of new track concepts that will be carried out in task T1.1.2.

2 OBJECTIVES

The overall objective of *SP1 – WP1.1 Modular integrated design of new concepts for infrastructures* is to design, develop and test new concepts for railway track, adapted to mixed traffic and eventually adaptable to very high speed, with the following particular distinct features:

- Cost and RAMS oriented design.
- Modular design in order to enable "Plug&Play" for rapid construction or maintenance.
- Adaptability of existing infrastructure to new freight requirements.
- Energy provision, telecommunications and signalling will be incorporated, whenever possible.

The main goal of the first task on this WP (T1.1.1) is to identify the specifications and develop new knowledge which will be used in the concepts and designs developed in later tasks, in particular the following:

- To identify market and environmental requirements, the latter with information from SP5, and review flexible/adaptable infrastructure design concepts.
- To develop a combined design to cost and RAMS methodologies for the new systems design and development using data and methods from SP5, using also feedback from infrastructure service.
- To develop a deeper knowledge on track actual loads during service loads in view of a more accurate assessment of the track cumulative damage, hence a better targeted maintenance.
- To develop new knowledge and guidelines for design for the track (including substructure) resilience to natural events (mainly floods, in particular thermo-hydro-mechanical calculations.
- To incorporate noise and vibration performance from the start of the design process.
- To identify the constrains induced by the Plug&Play concepts in the design, the constrains induced by the embedded energy provision, telecom and signalling equipment in the design.

Based on the outcomes of the above mentioned tasks, this deliverable reports the design requirements and improved guidelines for design (track loading, resilience and reliability). The new concepts generated according to these requirements shall be a step forward in track design, leading to the enhancement of infrastructure capacity, which is one of the main challenges of the C4R project.

At the time being, the new track systems are not required to be fully compatible with current regulatory frameworks, but the TSIs are a good starting point to pave the way for the homologation of the new developed systems. Most of the requirements arising from these regulations depend on the category of the line, as described in section 9.1. According to the general objective of the WP, the new developed track systems shall be suitable for high speed and/or mixed traffic, therefore the following categories have been selected:

- Category I: High-speed lines. New lines for speeds of at least 250 km/h.

- Category IV-M: Conventional rail lines. New core TEN lines. Mixed traffic.

As a first approach, the new track design shall address the solution on plain tracks. The solutions for transition zones and S&C require specific requirements that are out of the scope of this document.

According to this description of objectives, the structure of this report is shown in Table 1.

Table 1. Structure of this report

CHAPTER	TITLE	CONTENT OF CHAPTER
1	Introduction	
2	Objectives	The objectives of WP1.1, T1.1.1 and this report.
3	Context	Why slab track? A quick review of the state-of-the-art.
4	Geometrical requirements	
5	Mechanical requirements	
6	Environmental requirements	
7	Construction requirements	
8	Maintenance requirements	
9	Operational/safety requirements	
10	Cost requirements	
11	Requirements from the Track Loading Design Guideline	Brief summary of the Track Loading Guideline and requirements derived from it.
12	Requirements from the Climate Resilience Design Guideline	Brief summary of the Climate Resilience Guideline and requirements derived from it.
13	Requirements from the Cost & RAMS oriented Design Guideline	Brief summary of the RAMS Guideline and requirements derived from it.
14	Conclusions	
15	References	
Annex I	Track Loading Design Guideline	Paper
Annex II	Track resilience to natural events Design Guideline	Paper
Annex III	Cost & RAMS oriented Design Guideline	Paper

3 CONTEXT

Although most of the current railway tracks are still of traditional ballasted type, recent applications tend more and more towards slab track. The major advantages of slab track are: low maintenance, high availability, low structure height, and low weight. In addition, recent life cycle studies have shown that from the cost point of view, slab tracks might be very competitive.

Experiences in high-speed operation have revealed that ballasted tracks are more maintenance intensive. In particular, ballast pick-up at speeds of about 275 km/h and more caused by aerodynamic forces/very high wind speeds and air turbulences in the space between the train's underfloor parts and the ballast surface, or –in wintertime, at speeds of more than 160km/h- by dislodged ice-build-up (ice falling down from the train's underfloor parts), serious damage can occur to wheels and rails. The flying ballast stones can destroy parts of the running and braking gear, underfloor ETCS antennas and can get between wheel tread and rail top, there causing railhead defects which result in a rapid deterioration of track geometry.

The track-geometry stability required for the use of eddy-current brakes furthermore makes additional measures necessary, or the implementation of especially difficult track-superstructure solutions.

An increase in train speed is accompanied by disproportionately great increases in effective vertical vibration velocities in the ballast and the track structure. These phenomena accelerate the process of track-geometry impairment. To face this problem, it is possible here to employ counteractive measures to enhance track elasticity, but the consequences are considerable higher costs and an increase in the space required for the track. These disadvantages more than outweigh the original cost benefits of ballasted track over slab track solutions.

Owing to the superior geometry quality obtained in the manufacture of slab tracks and to the outstanding track-geometry stability throughout the entire lifecycle, these track types allow more direct line routing that is more satisfactorily adapted to the terrain (i.e. with tighter radii, steeper gradients and fewer civil constructions). In the final track layout, shorter tunnels and bridges and lower structure heights results in huge savings in civil constructions, which can compensate the additional costs for the initial construction of slab track compared with the ballasted solution.

As a result, the application of slab tracks for the new construction of high-speed rail lines over the past 10 to 15 years has developed from a customized design solution for niche applications (for example, in tunnels, on bridges, or in track sections near train stations) to standard, end-to-end technology for superstructure solutions on lines with demanding requirements and high loads.

In the design of railway lines factors like life cycle cost, construction time, availability and durability play an increasingly important role. The new track concepts to be developed in the

C4R project are required to have low LCC and high RAMS assessment, so the designs are necessarily in the scope of slab track systems.

The new track infrastructure concepts are asked to be completely new generated; nonetheless it is useful to overview the description, strengths and drawbacks of the existing solutions as a starting point for the design. The new developments must share, even enhance, the benefits of current track systems, while minimizing or avoiding the drawbacks in order to ensure a real step forward in railway infrastructure design.

According to the design and construction characteristics, slab track systems can be categorized as shown in Figure 1.

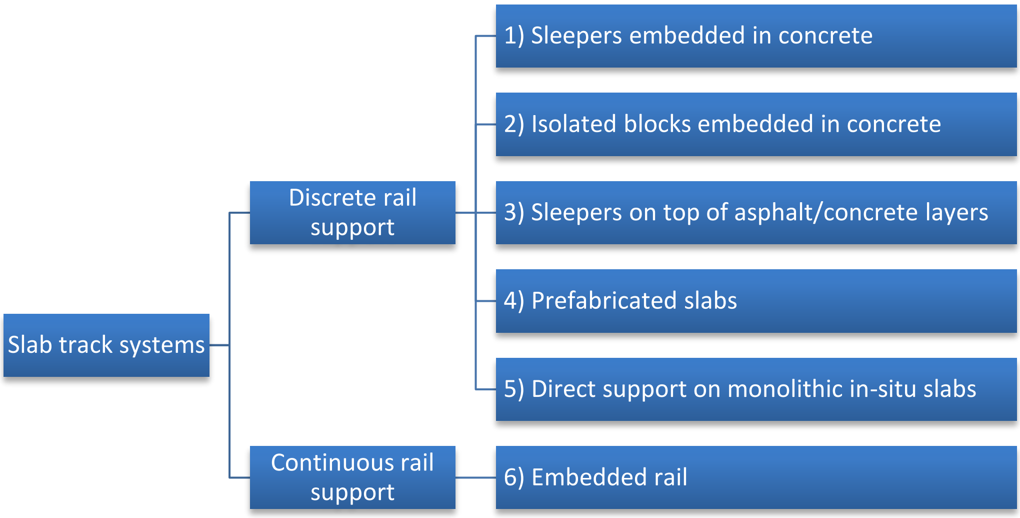
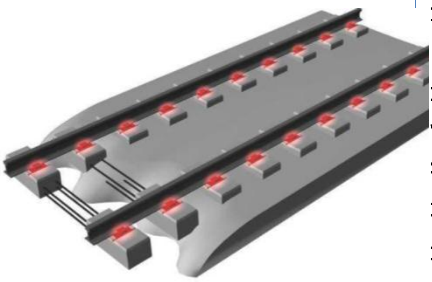
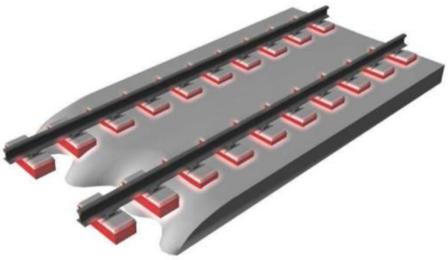


Figure 1. Main types of slab track systems

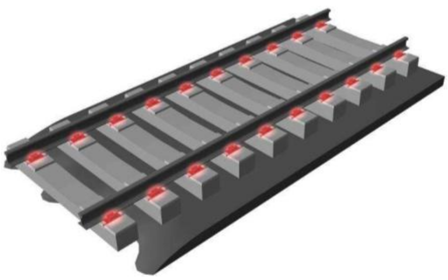
Following tables describe the main characteristics and the commercialized systems within each one of these six types. The most popular slab track designs worldwide according to the total length constructed in 2012 are FF Bögl (4391km), Shinkansen (3044km), Rheda (2205km), LVT-Sonneville (1031km), Züblin (606km), Stedef (334km) and Infundo-Edilon (211km) [1]. It is not worthy to go into detailed descriptions of each slab track system, the reader can look up the following references for further information: [2] [3] [4] [5]

1) Sleepers embedded in concrete	
Description: Sleepers cast into concrete inside a concrete trough or directly on top of a concrete roadbed.	*Characteristics:* > Top-down track alignment > Mostly reinforced > No additional devices for adjustment of the mutual rail position (rail inclination, gauge) required > Anchorage of rail fastening elements in pre-fabricated, high quality concrete > Durable and firm bond of sleepers / supporting blocks with the track slab (also depending on kind of used sleepers / supporting blocks) > Easy exchange of wearing parts (rails, elastic elements) > Post-adjustment of the vertical and lateral track position only possible within the rail fastening elements > Effort and time consuming removal and repair
Figure: 	
Examples: Rheda, Rheda-Berlin, Rheda 2000, Rheda City, Heitkamp, Züblin, SBV	

2) Isolated blocks embedded in concrete	
Description: Elastically encased supporting blocks poured into an in-situ concrete slab.	*Characteristics:* > Top-down track alignment > Reduction of vibrations due to the complete elastic isolation of the supporting blocks from the concrete slab > Additional devices for adjustment of the mutual rail position (rail inclination, gauge) always required (e.g. gauge bars) > Reduced stresses on the elastic elements due to large bearing area > Anchorage of rail fastening elements in pre-fabricated, high quality concrete > Easy exchange of supporting blocks > Exchange of elastic elements only possible after removing of supporting blocks > Post-adjustment of the vertical and lateral track position possible within the rail fastening elements or by repositioning of supporting points
Figure: 	
Examples: Soneville (LVT), Stedef, WALO, EBS	

<table>
<tr><th colspan="2">3) Sleepers on top of asphalt/concrete layer</th></tr>
<tr><td>Description:

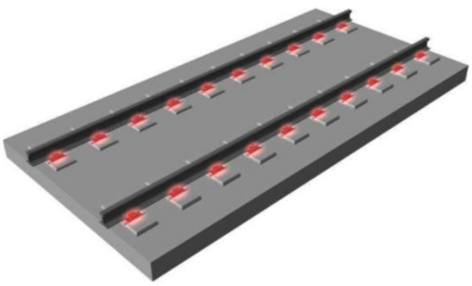
Sleepers borne directly on top of an asphalt or concrete layer</td><td rowspan="3">Characteristics:

> Bottom-up track alignment
> High quality bottom layer required
> The system can perform slight plastic adaptations when it is needed (in asphalt base solutions).
> No additional devices for adjustment of the mutual rail position (rail inclination, gauge) required
> Usually post-adjustment of the track position (due to the bottom-up track alignment) required, possible within the rail fastening elements or usually by repositioning of sleepers
> Usually re-calculation of the gradient required (to limit the post-adjustment effort by using adjustment plates)
> Anchorage of rail fastening elements in pre-fabricated, high quality concrete
> Easy exchange of sleepers
> Easy exchange of wearing parts (rails, elastic elements)</td></tr>
<tr><td>Figure:
</td></tr>
<tr><td>Examples:

ATD, BTD, GETRAC, Walter, Nantenbach , SATO, FFYS</td></tr>
</table>

<table>
<tr><th colspan="2">4) Prefabricated slabs</th></tr>
<tr><td>Description:

Reinforced or pre-stressed precast concrete slabs</td><td rowspan="3">Characteristics:

> Top-down track alignment
> No additional devices for adjustment of the mutual rail
position (rail inclination, gauge) required
> Higher quality due to the industrial manufacturing process
> Anchorage of rail fastening elements in pre-fabricated, high quality concrete
> Easy exchange of wearing parts (rails, elastic elements)
> Intricate transport and logistics
> High-level of mechanisation possible
> The use of prefabricated elements avoid having to process wet concrete during construction
> Intricate exchange of the concrete slab track elements or plates (depending on the system)
> Danger of systematic failures
> It consumes considerable height and is expensive.</td></tr>
<tr><td>Figure:
</td></tr>
<tr><td>Examples:

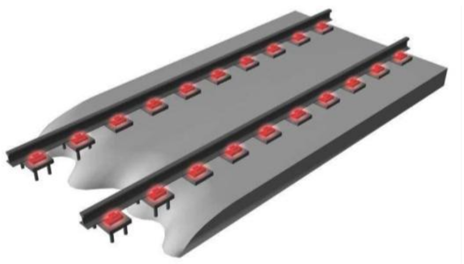
J-Slab (Shinkansen), IPA, FF Bögl, OBB-Porr, Railtech (floating slab), FST</td></tr>
</table>

5) Direct support on monolithic in-situ slabs

Description:

Continuous monolithic concrete layer and direct rail fastenings adjusted on it

Figure:



Examples:

Lawn track, FFC, Hochtief, BES, BTE-BWG/Hilti, PACT, Direct rail fastening (Vossloh DFF 300, Pandrol VIPA-SP, Dubai, Ironless, Vanguard, AHD, etc.)

Characteristics:

> Top-down track alignment

> Additional devices for adjustment of the mutual rail position (rail inclination, gauge) always required (e.g. gauge bars)

> Anchorage of rail fastening elements in usual in-situ concrete

> Reduced stability of the track panel during placing of concrete

> Easy exchange of wearing parts (rails, elastic elements)

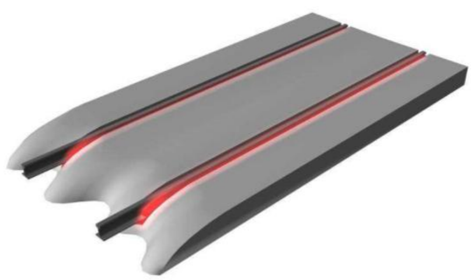
> Well experienced staff required

6) Continuously embedded/supported rails

Description:

Continuously elastically supported rail by means of a compound such as cork or polyurethane which surrounds almost the entire rail profile except the rail head.

Figure:



Examples:

Edilon-Infundo, DeckTrack, BBERS (Balfour Beatty), CDM-CoconTrack, Grooved-ERL (Phoenix), Vanguard, KES,

Characteristics:

> Top-down track alignment

> Difficult / demanding installation

> Additional devices for adjustment of the mutual rail position (rail inclination, gauge) always required (e.g. gauge bars)

> Continuous rail support

> Absence of dynamic forces due to secondary bending between single rail supports.

> Reduced noise production.

> Increase in life span of the rails, and further reduction of maintenance with respect to discrete support.

> Reduced construction height on road crossings, so that embedded rail provides a smooth and obstacle free surface for crossing traffic.

> Extremely high rail sliding resistance (no application on

long bridges)

6) Continuously embedded/supported rails	
Ortec, Saargummi, SFF	> No turnout solutions > Special materials required > Intricate exchange of wearing parts (rails, elastic elements / pouring compound) > Few references on high-speed and freight traffic.

4 GEOMETRICAL REQUIREMENTS

4.1 COST-EFFECTIVE TRACK AND LAYOUT PARAMETERS

Apart from the reduced maintenance needs, one of the main economic advantages of slab track systems against traditional ballasted track is that the first ones allow more cost-effective track layout, as narrower curves with high superelevation and higher cant deficiency can be applied.

On ballasted track, the non-compensated lateral acceleration in curves is limited because of the limited lateral resistance provided by ballast. On slab track, the resistance to lateral loads is quite higher due to the good skid resistance between the slab and the base layer and, in some slab track systems, thanks to specific stoppers which transmits horizontal forces. It allows increasing the superelevation and cant deficiency associated with a reduction of alignment radius, or higher speed on an existing alignment radius.

In some cases, this adaptability to topographical constrains has been a key factor in the selection of track system for new or upgraded lines. As an example, the new route Cologne-Frankfurt, which was constructed in part parallel to the existing motorway Autobahn A3, was opened in 2002 for 300km/h traffic, with a minimum radius of 3.350m and a cant of 170mm. The cant deficiency is about 150mm, resulting in an unbalanced lateral acceleration of 1 m/s^2. A slab track structure was a prerequisite for this; the type was 'Rheda' modified with monoblock sleepers and twin block grid sleepers, and also the 'Züblin' ladder track type [6].

Unfortunately, the current TSIs do not take into account this important advantage of slab track systems. There is only a slight distinction in these regulations between ballasted and slab tracks when selecting the cant deficiency: The high-speed infrastructure TSI [7], article 4.2.8.1, allows to decrease the maximum cant deficiency from 130 to 80mm when running at the speed range 250- 300km/h on lines of Category I.

Table 2 shows the whole set of track parameters stated in the relevant TSIs [7] [8].

Table 2. TSI Track parameters

PARAMETER	HIGH SPEED	MIXED TRAFFIC
Line category	I	IV-M
Nominal track gauge	1435 mm	
Track cant	200 mm	160 mm
Max cant deficiency (for trains without compensation systems)	150 mm (250 < V < 300 km/h) 80 mm (300 < V ≤ 350 km/h)	130 mm
Equivalent conicity	0,20 (250 < V ≤ 280 km/h) 0,10 (280 < V ≤ 350 km/h)	0,25
Railhead profile (plain line)	UIC 60 E2 (for novel designs see Figure 2-left)	See Figure 2-right
Rail inclination (plain line)	1/20 to 1/40	

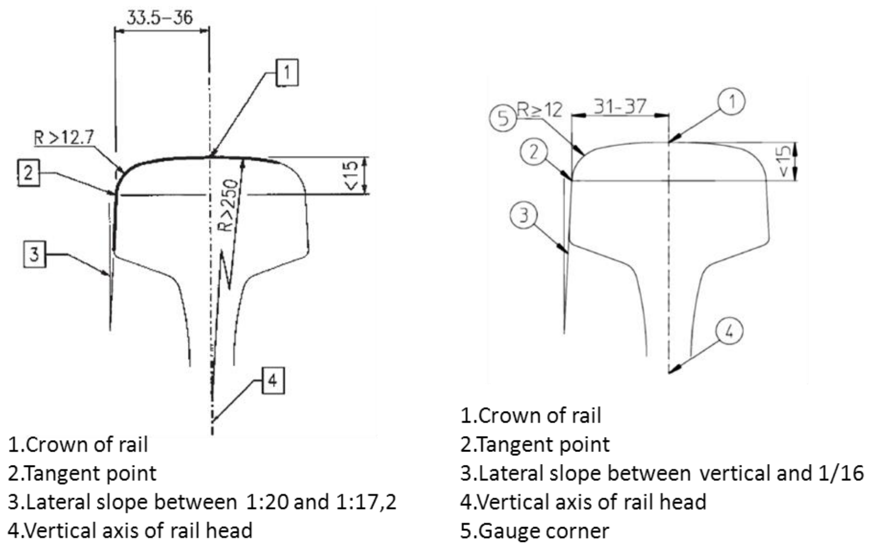


Figure 2. Requirements on rail head profile for high speed lines (left) and conventional (right) [7] [8]

The line layout parameters are derived from track parameters and from the characteristics of the rolling stock. Table 3 shows to the alignment parameters, as set out in the TSIs [7] [8].

Table 3. TSI Line layout parameters

PARAMETER	HIGH SPEED	MIXED TRAFFIC

PARAMETER	HIGH SPEED	MIXED TRAFFIC
Line category	I	IV-M
Minimum structure gauge	GC reference kinematic profile (see Figure 3)	
Distance between track centers	4,20 m (250 < V ≤ 300 km/h) 4,50 m (300 < V ≤ 350 km/h)	4,0*
Maximum gradient	35 ‰	12,5 ‰
Minimum radius of horizontal curve	2900 m (250 < V ≤ 300 km/h) 4950 m (300 < V ≤ 350 km/h)	1550 m
Minimum radius of vertical curve	600 m (crest); 900m (hollow)	

* Depending on track gauge.

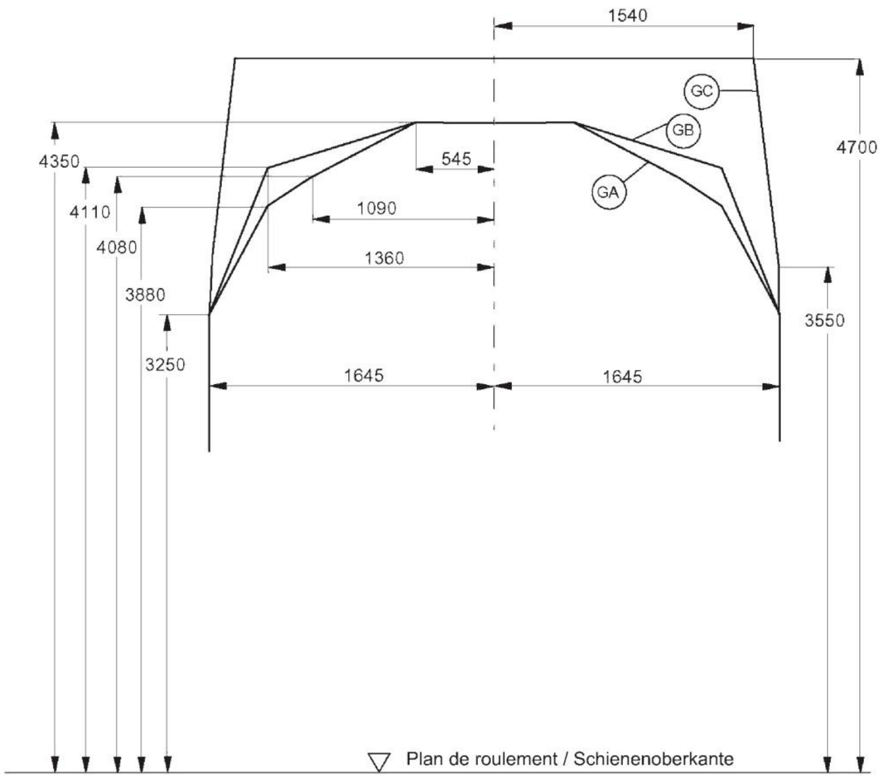


Figure 3. Kinematic gauge reference profiles [9]

Table 4 shows the track layout parameters in some of the slab track lines around the world. It can be observed that almost all these parameters are between the thresholds of the TSIs.

Table 4. Track layout parameters in existing lines with slab track

LINE (COMPANY, INAUGURATION)	TRAFFIC	MAX V (KM/H)	MAX CANT (MM)	MAX CANT DEFICIENCY (AT MAX V) (MM)	MIN R (M)	MAX GRADIENT (‰)	MIN VERTICAL CURVES (M)
Tokaido (JR, 1964)	Passenger	270	180	50	2.500	20	10.000
Sanyo (JR, 1972)	Passenger	300	180	20	4.000	15	15.000
Tohuku (JR, 1982)	Passenger	270	200	45	4.000	12	15.000
Joetsu (JR, 1982)	Passenger	320	200	45	4.000	15	15.000
Hokuriku (JR, 1997)	Passenger	260	200	45	4.000	15	-
Diretissima Rome-Florence (FS, 1977)	Mixed	250	125	120	3.000	7,5	20.000
TGV Sud-Est Paris-Lyon (SNCF, 1983)	Passenger	270	180	35	4.000	35	25.000
Mannheim-Stuttgart (DB, 1987)	Mixed	250	65	80	5.100	12,5	25.000
Hanover-Würzburg (DB,1988)	Mixed	250	45	60	7.000	12,5	25.000
TGV Atlantique (SNCF, 1990)	Passenger	300	150	30	6.000	25	16.000
Cologne- Frankfurt	Passenger	300	170	150	3.350	40	11.500
Seoul-Pusan (KNR, 2003)	Passenger	300	130	65	7.000	25	-
HSL Zuid (R, 2009)	Passenger	300	180	100	4.000	25	12.000

LINE (COMPANY, INAUGURATION)	TRAFFIC	MAX V (KM/H)	MAX CANT (MM)	MAX CANT DEFICIENCY (AT MAX V) (MM)	MIN R (M)	MAX GRADIENT (‰)	MIN VERTICAL CURVES (M)
Nuremberg-Ingolstadt (DB, 2011)	Passenger	300			3.700	20	

The new slab track systems shall be designed according to the geometrical requirements stated in the TSIs, in particular those related to the track (see Table 2) and the line layout (see Table 3).

4.2 REDUCED HEIGHT AND WEIGHT

Bridges and tunnels are a relatively rigid foundation for ballast beds, therefore to achieve the necessary stiffness it is required to increase the thickness of the ballast layer, which could lead to heavy and high track structure requiring stronger constructions for bridges and viaducts, as well as larger cross sections in tunnels. A usual solution in ballasted track is to provide the additional elasticity by the application of ballast mats or high elastic fastenings.

The application of slab track in tunnels and bridges is very efficient in terms of construction, durability, strength and economy. On these rigid structures, the hydraulically bounded layer (HBL) is not required (see Table 5) and the overall height of the track can be reduced consequently.

In case of tunnels, the asphalt or concrete bearing layer may be laid directly on the tunnel base and its thickness can also be reduced, achieving important reductions of the tunnel cross-section compared to traditional ballasted track (see Figure 4). In the case of upgrading an existing route, e.g. for electrification or increasing structural gauge, expensive track lowering works can be avoided.

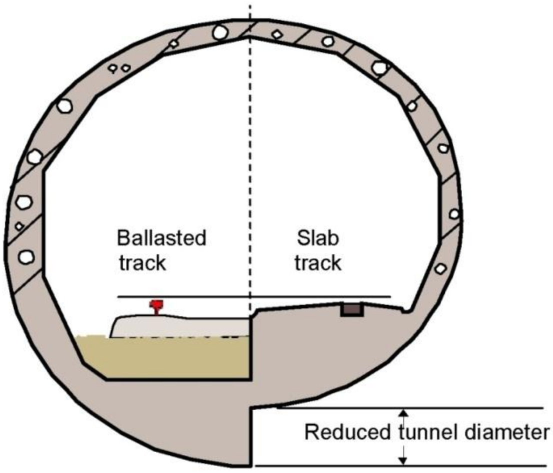


Figure 4. Reducing cross-section at tunnels

Due to a rigid track foundation on tunnels, not only the thickness of slab track can be reduced, the reinforcement can be also optimized. For instance, the reinforcement of Rheda 2000 can be reduced up to 50% compared with standard application on embankment.

In case of bridges, the height of the track is also important for the structure design because it is quite related to the linear weight of the system. Slabs and reinforced layers are considered death loads in bridges calculation. The lighter the slab track, the lower the structural requirements on bridges and the cheaper their construction cost. Table 5 shows the height and weight per meter in most of the existing slab track systems.

Table 5. Height and weight of different slab track systems [2] [3] [4] [10]

Slab track system	Overall height (mm)	Overall height in tunnels and bridges (mm)	Hidraulically bounded layer (mm)	Asphalt base layer (mm)	Weight (tn/m)
Rheda	931	631	300	-	2,3
Rheda-Berlin	951	651	300	-	2,4
Rheda 2000	772	472	300	-	1,5
Heitkamp	1061	761	300	-	2,9
Züblin	899	599	300	-	2,1
SATO	909	609	300	300	2,2
FFYS	909	609	300	300	2,2
LVT standard	752	452	300	-	1,4
LVT low profile	712	412	300	-	1,2
ATD	1021	721	300	300	2,7
BTD	929	629	300	-	2,3
Walter	929	629	300	-	2,3
GETRAC	1021	721	300	300	2,7
Lawn Track	807	507	300	-	1,7
FFC	777	477	300	-	1,5
Hotchief	822	522	300	-	1,8
BES	761	461	300	-	1,4
BTE	761	441	320	-	1,3

Slab track system	Overall height (mm)	Overall height in tunnels and bridges (mm)	Hidraulically bounded layer (mm)	Asphalt base layer (mm)	Weight (tn/m)
PACT	701	401	300	-	1,1
INFUNDO	694	394	300	-	1,1
FF Bögl	774	474	300	-	1,5
ÖBB-Porr	800	500	300	-	1,6
Shinkansen	715	415	300	-	1,2

Figure 5, built on values from Table 5, shows the contribution of each base layer and the slab track itself to the overall height of the system. Almost all of them use a 300mm height hydraulically bounded layer, which could be omitted in bridges and tunnels.

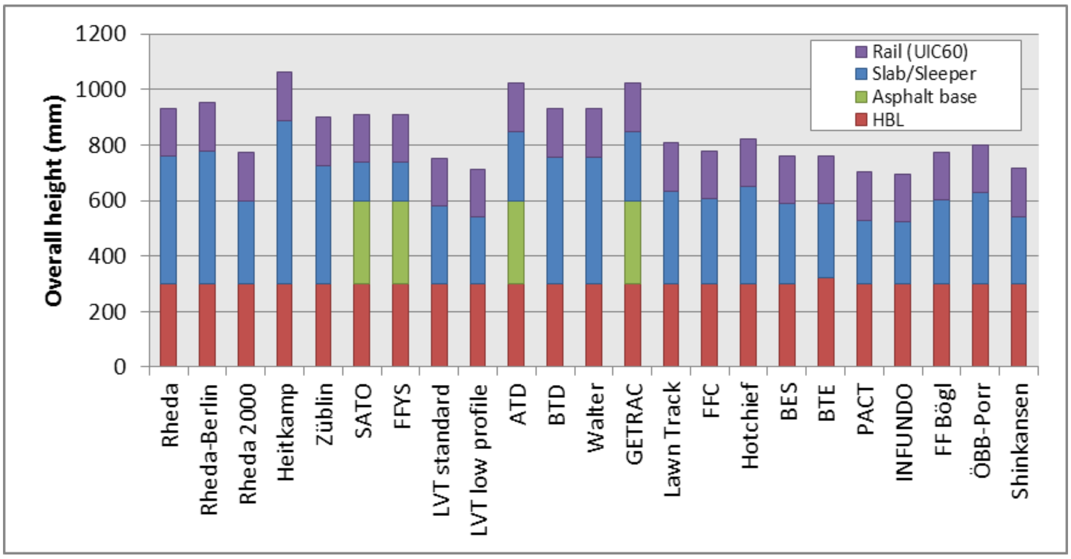


Figure 5. Overall height of different slab track systems

In order to be competitive enough in terms of required cross section in tunnels and bridges resistance, the overall height of the new slab track designs should be below 800mm, including base layers.

4.3 Enough space for signalling and electro-technical equipment

The signalling equipment installation must be erected and installed in place hence free spaces have to be provided in advance. The same apply for the electro-technical installations and integrated monitoring systems hence their planning has to be completed prior to the construction of the slab track.

4.4 EARTHING OF THE METALLIC PARTS

A special feature of slab track systems, compared to the ballasted track, is that reinforcement parts, if present, have to be well connected to each other electrically in order to prevent the occurrence of voltage differences. Therefore, the reinforcement of slab track has to have such dimensions as to safely lead away reverse current and short circuits without destroying or damaging the structure. Reinforcement parts have to be earthed at each catenary pole or, in some extreme cases, to a band earthing connection laid in the earth parallel to the line.

In any case, the geometrical design of track structure shall also take into account interfaces possible ground linkage of metallic reinforcements.

4.5 ELECTRICAL ISOLATION OF THE RAILS

Electric traction vehicles of standard railways are supplied by the catenary. The operational currents have to be led back via the rails and, partially in parallel, through the earth. The permitted voltage difference between the surrounding earth and the rail must not exceed a certain human contact voltage depending on time. Therefore, a lower diffusion resistance has to be the aim.

On the other hand, a high bedding resistance between the two rails is desirable for signalling equipment. These two contrary requirements have to be coordinated for track design.

According to the TSI [8], the design value of minimum electrical insulation of rails shall be 3Ωkm in wet condition. The fastening systems available in the market usually can ensure this insulation performance between the rails. In some cases, such as the LVT slab track system, this requirement led to leave out the tie-bars included in the first versions.

Finally, if the railway current supply is designed for traction currents of more than 1200A, return cables have to be laid from mast top to mast top. In this case, the requirements for rail isolation could be lower, although still necessary.

4.6 FACILITATION OF DRAINAGE

Drainage of slab tracks is a critical requirement, as it is source of many maintenance problems. In ballasted tracks, the use of separated sleepers, unbound bearing layers (ballast and subballast) and transversal slope ensures that water leaves out the track and goes to parallel culverts. In case of slab tracks, the evacuation of water between the sleepers and between parallel lines may require additional drainage channels. As an example, Figure 6 shows a comparison between typical cross section on ballasted tracks and slab track (Rheda) design. It can be observed that water between parallel slabs require an additional central drainage tube.

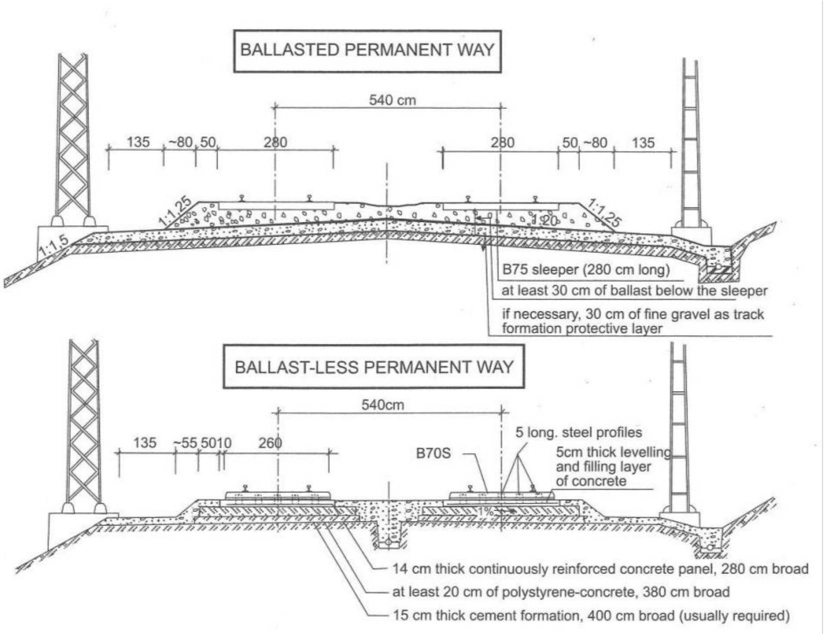


Figure 6. Comparison between standard cross section of ballasted track and slab track Rheda design [3]

In case of precast slab systems, with the aim of draining the slab surface it is a usual requirement to provide a transverse slope in the design. For example, in the FF Bögl system every slab is manufactured with a transverse slope of 0.5% by default. In addition, for wagon and locomotive washdown yards, this system offers a special prefabricated slab element in the siding area (see Figure 7), provided with a central groove which offers the possibility to drain soiled washing water in a targeted and environmentally friendly way.

Figure 7. Special FF Bögl slab for washdown yards

On the other hand, cross section in tunnels usually require two drainage tubes, which is quite space-consuming. However, it is also possible to drive collected water to a unique duct, as shown in Figure 8.

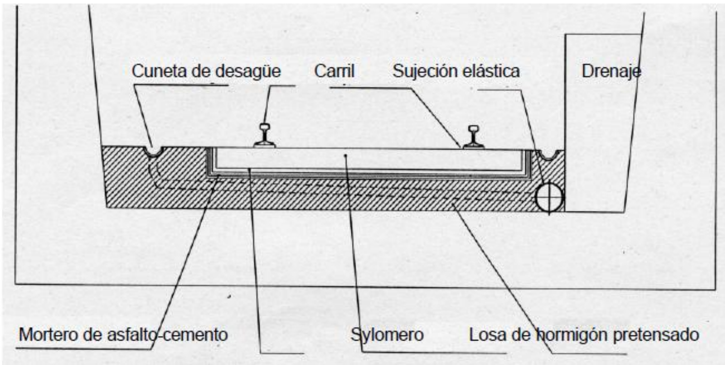


Figure 8. Drainage of slab track with a culvert and a unique lateral tube [11]

5 MECHANICAL REQUIREMENTS

5.1 NON-SETTING SUBSOIL

In slab track systems, the ability to make adjustments to the track geometry after construction is finished is relatively limited. Larger alterations in track position and superelevation can only be made possible by substantial amounts of work. According to the possibilities offered by adjustable fastening systems, only simple corrections up to 26mm in vertical position and 5mm in horizontal position are possible to counteract small deformations. As a consequence to the small adaptability of slab tracks, any settlement in the embankments must try to be avoided.

In order to prevent this problem, settlements predictions in the design phase shall show, not only how fast construction is to proceed, but also demonstrate that settlements occurred after the line is opened are small enough to be rectified according to adjustable fastening capacity or other technical method. Recent studies [12] conclude that long term differential settlements can be tolerated in very long embankments by considering the possibility to create a vertical transition curve according to the line speed (alignment rule) and presence of structures with pile foundations.

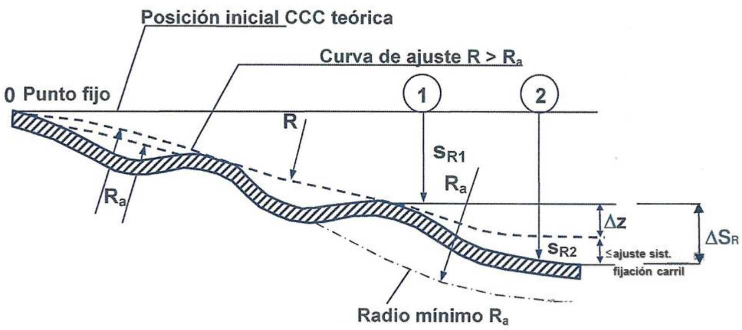


Figure 9. Adjustment of vertical curvature to face settlements on long earth works

When settlement criteria cannot be achieved, strengthen methods in the subsoil must be applied. That is the case of poor soils (e.g. clayey soils) which present potentially collapsible behaviour. In the presence of water, these soils typically expand, however, in cases when high stress are combined with relatively low saturation levels, collapses may occur resulting in excessive deformation of the substructure. In areas where soft soils are predominant it is recommended to excavate these poor soils replacing it for good quality ones. In case of large deposits the excavation of these soil layers might be very expensive. These excavation works may be avoided by adopting a track on pile systems (see Figure 10) or enhancing the subgrade soil with piles of different materials (e.g. cement, flue ash or gravel) where the track superstructure is supported by a reinforced concrete slab which is founded directly on piles. The loads are distributed by the slab track and then transferred by the concrete slab to the piles. There is no influence caused by problematic subgrade soils which is used as filling material. This type of solution effectively stabilizes long-term settlements of the substructure.

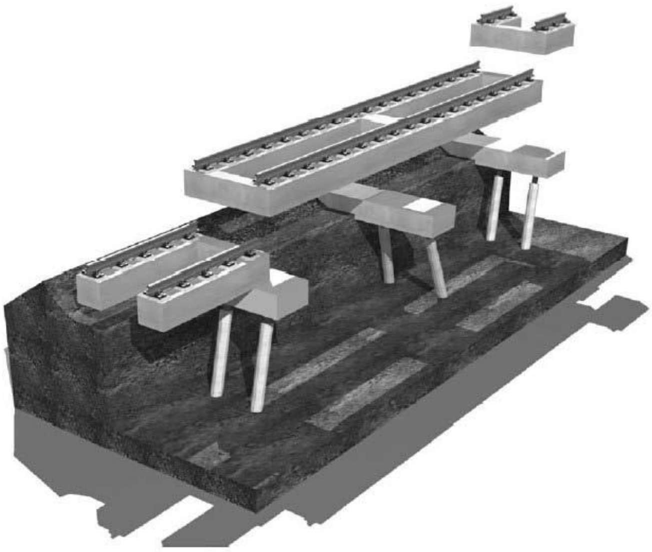


Figure 10. Deep track foundation for NFF slab track (thyssenKrupp) [13]

5.2 HIGH QUALITY OF SUPPORTING STRUCTURE

According to the UIC 719 leaflet "Earthworks", the slab track system on earthwork can generally be separated in 3 subsystems:

- The track components
- The supporting structure
- The earth work, including the subsoil and frost protection layer

The supporting structure is in many cases made with a reinforced concrete slab; it can consist of unreinforced concrete or asphalt layer too. This structure should be continuous and monolithic for design. The limit between the track components and the supporting structure has to be assessed considering the continuity of concrete. So prefabricated concrete slabs which remain separated are considered as part of the track components subsystem and not part of supporting structure subsystem. On the contrary, prefabricated slabs which are strongly linked mechanically can be designed as supporting structure. In any case, the layers used for adjusting geometry of track during construction process should not contribute to the resistance of supporting structure if they are not poured in the same operation as supporting slab or if different material as bituminous mortar is used.

Every manufacturer set particular requirements for the quality of materials and thickness of every layer in the supporting structure for slab tracks. There is no agreement or regulation at European level, although most of infrastructure managers follow the German requirements for slab track concerning substructures of existing and newly constructed tracks, as shown in Table 6 [14]:

Table 6. Requirements regarding quality of the substructure for slab track

Bearing layer	Newly constructed track	Existing track	Layer thickness
Reinforced concrete roadbed	Concrete quality: B 35 Reinforcement percentage: 0.8-0.9%		Depends on E_{v2} (approx. 200mm)
Asphalt roadbed	Binder B 80 or B 65, top layer PmB 65		Depends on E_{v2} (approx. 300mm)
Concrete roadbed	The necessity must show in the design calculations for the substructure		If necessary (approx.. 300mm)
Frost protection layer	E_{v2}≥120 MN/m^2	E_{v2}≥100 MN/m^2	
Embankment	E_{v2}≥60 (55) MN/m^2	E_{v2}≥45 MN/m^2	

*E_{v2}: Deformation modulus resulting for static plate load testing.

5.3 High quality of earth work

As explained in section 5.1, slab track does not admit important settlement of the soil support. It is therefore imperative that the settlement of embankments newly constructed is nearly finished at the time of the construction of the track. Adjustable fastening systems should not be used for continuous long-term settlements with foreseeable character. Zones of long-term compressible soils must be cleared on structures like railway bridges.

The sublayers must be homogeneous and capable of bearing the imposed loads without significant settlements. In case that the bearing capacity is inadequate, the earth work sub-system shall include reinforcement layers. This results in high construction costs of the earthworks.

For instance, in Germany a lot of effort is being made to obtain a stable embankment [2]. The regular composition of layers consists of improved ground (through compacting or hydraulic stabilising) followed by a frost-protection layer of granular materials. A similar section is defined in Spain for high speed tracks; in this case the standard is for lime-stabilized embankments [15].

The quality of an earth work is highly dependent on the compaction process defining the initial conditions after construction. When subjected to traffic loading and environmental actions, the deformational behaviour of subgrade soils depends on its previously loading history, particularly on the maximum preconsolidation stress ever applied to the soil. An adequate compaction process must ensure that the compaction stress is higher than the expected maximum stress that will ever be applied to the soil. Furthermore, the compaction of the soil must be performed at the wet of the Modified Proctor (MP) optimum.

The compaction should achieve a minimum deformation modulus with an homogeneous distribution. The degree of compaction is usually related to a reference test: Standard Proctor (SP) or Modified Proctor (MP). The latter is becoming more common in some countries for high speed lines and high embankments. The degree of compaction and minimum deformation modulus to be considered in each subgrade layer during the design, are shown in Table 7.

Table 7. Mechanical characteristics of the earthwork (UIC Leaflet 722) [16]

LAYER	DEGREE OF COMPACTION	DEFORMATION MODULUS	RATIO
Embankment fill	$\rho_d \geq 95\%$	$E_{v2} \geq 45$ MN/m^2 (fine soils) $E_{v2} \geq 60$ MN/m^2 (sandy and gravelly soils)	$E_{v2}/ E_{v1} \leq 2,2$
Prepared subgrade or form layer	$\rho_d \geq 100\%$ (SP) $\rho_d \geq 95\%$ (MP)	$E_{v2} \geq 80$ MN/m^2	$E_{v2}/ E_{v1} \leq 2,2$

*E_{v1}, E_{v2}: Deformation modulus resulting for static plate load testing.

The elastic modulus at the top-surface of the substructure E_{v2}, which determines the thickness of the upper layers, can be increased by dynamic compacting and mix-in-place ground-improvement, for instance with chalk and cement or by ground-replacement. The geotechnical requirements for the embankment shall be satisfied for a depth below the rail head level when the Proctor densities are:

- Newly constructed track: ≥3.0 m with D_{pr}=0.98-1.00
- Existing track: ≥2.5 m with D_{pr}=0.95-1.00

Transitions zones between earthworks constructions and rigid structures such as bridges and viaducts present high variations of the vertical stiffness which leads to divergent long term deformational behaviour. In the long run, this divergence results in differential settlements of the slab track eventually leading to concrete cracking and track geometry deterioration which is worsened at each train passage and aggravated by the exposure to atmospheric actions. Hence, transition zones from slab track on bridges to adjacent slab track at embankments, cuttings and tunnels or even ballasted track sections have to be designed in order to assure good smooth transition of the vertical stiffness avoiding damages due to dynamic effects and future unwanted maintenance needs. Nonetheless, the design of transition zones is out of the scope of this deliverable, as the new track concepts will be developed, a priori, for plain lines.

The behaviour of the substructure is significantly controlled by environmental conditions which are associated to thermo-hydro-mechanical processes occurring between the atmosphere and railway trackbed layers. According to local hydro-geological and climatic characteristics, the design of the substructure must account for instability problems due to rainfall events and snow melting processes with particular focus on extreme scenarios where the duration, intensity and frequency of these phenomena must be adequately considered.

5.4 ADEQUATE TRACK STIFFNESS

Stiffness is still an open point in the TSIs. On traditional track, the ballast bed provides approximately half the resilience needed to absorb dynamic forces; the other half is provided by the subgrade. The stiffness of the overall track structure can be of the order to 100 kN/mm per sleeper which makes the rails deflects approximately 1mm under a 20-t axle load. A rail pad inserted between the rail and the sleeper filters out high frequency vibrations.

In slab track systems, the elastic rail pad and, if present, the undersleeper pad replace the ballast bed regarding its load-distribution and the damping functions. Therefore, the importance of the elastic pads is paramount for they become the only components in the track with elastic and damping properties.

The superstructure of each slab track system has different flexural stiffness; these are illustrated in Figure 11. Slab track constructions with low flexural stiffness can scarcely resist bending forces, the system rely completely on the bearing capacity and stiffness of the subsoil. In weak unreliable soils a slab track system with high flexural stiffness is essential to provide extra strength and adequate resistance acting as a bridge across weak spots and local deformations in the subsoil.

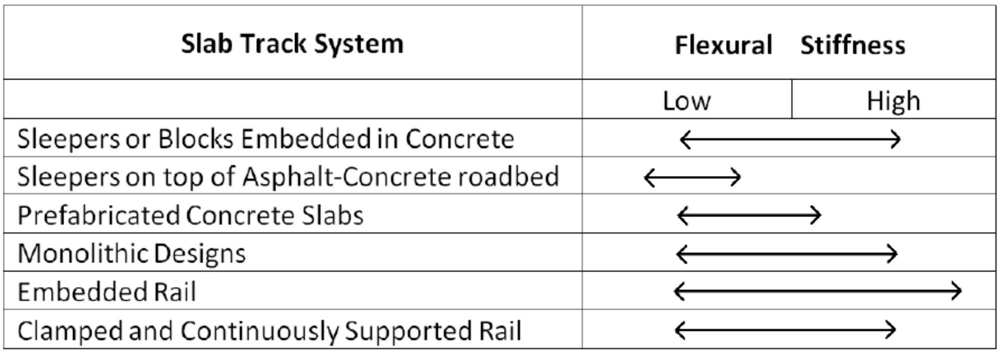
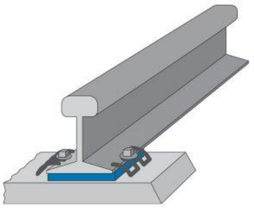
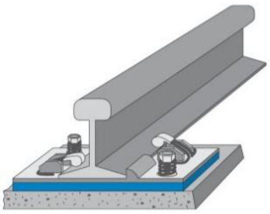
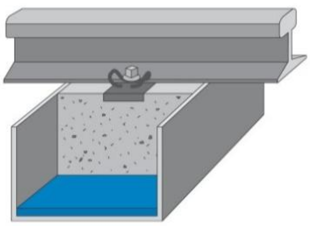
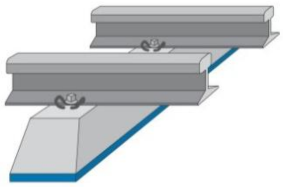
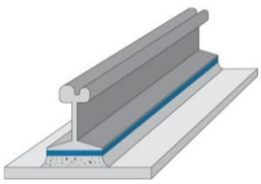
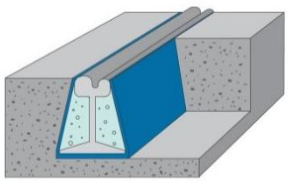


Figure 11. Approximate superstructure flexural stiffness for different track systems [2]

A wide range of options exists for the arrangement of elastic components (see Table 8).

Table 8. Elastic components for slab track systems

ELASTIC COMPONENTS	DESCRIPTION
Rail pads 	Elastic rail pads are placed directly under the rail base. The improved load distribution yields greater passenger comfort and less wear on the superstructure. The increased elasticity has a positive effect on the wearing of superstructure components and rolling stock.
Baseplate pads 	Specific solution for slab track systems. The base plate pads are installed between the grooved baseplate and the concrete slab. Elastic baseplate pads preserve the load-distribution function of the rails and reduce vibrations due to wheel and track irregularities. The railhead deflection during train passage can be reduced by adapting the stiffness distribution of the baseplate pad.
Insertion plates for sleeper boots 	One advantage offered by an elastically supported sleeper blocks is the reduced emission of air-borne sound because the vibration must travel through the additional support mass. A larger elastic support surface also results in lower edge pressure. The two levels of elastomers additionally reduce the pressures in the insertion pads and saves wear on the rail fastenings. The most frequent applications for this system are found in various types of tunnel sections.

Elastic components	Description
Sleeper pads 	Sleeper pads can be installed at the sleeper factory using an optimized joining system. This means that no additional work is necessary at the construction site. Installation takes place quickly regardless of the weather and with minimal line interruptions. Padded sleepers have proven themselves well, particularly for special track construction methods, such as for switches, crossings, transition areas and expansion compensation, and have become the technical standard in many countries.
Continuous rail support 	Continuous elastic rail base support provides an homogeneous stiffness. In some cases, it is able to compensate installation related height differences. It is a common solution for clamped rails.
Embedded rail 	The system completely envelops the rail. Lightweight yet resilient chambered filler components made from polyurethane are pressed against the rail web. Butting up – horizontally and vertically – against these filler components and the foot of the rail is an elastic bedding, which significantly reduces those superstructure movements that frequently lead to cracks in the rail surface. In addition to the cast for the joint, sealing lips seal off the top of the rail to prevent water infiltration.

The fastening systems for slab tracks usually include the railpad and the baseplate pads. This element provides the higher percentage of stiffness to the system, as well as the necessary deflection under wheel loading, as shown in Figure 12.

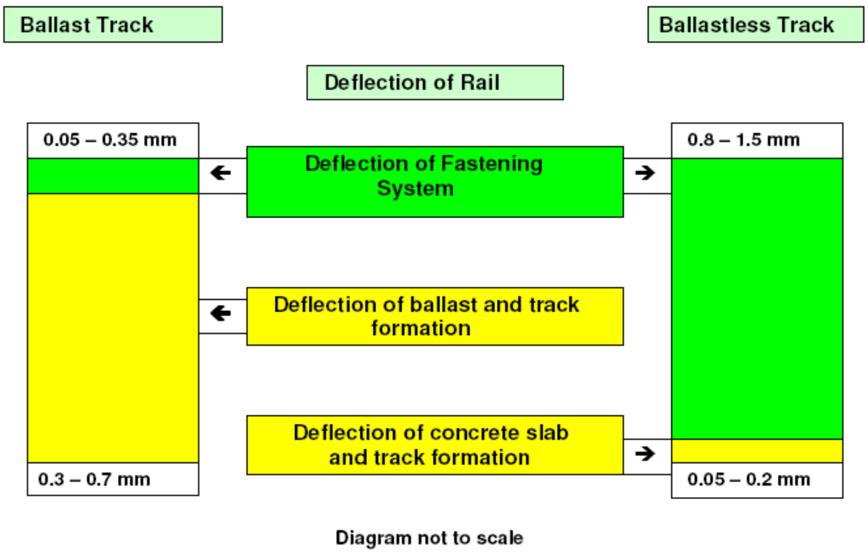


Figure 12. Rail deflection ballasted vs slab track [17]

For example, the system Vossloh 300 includes a high elastic rail pad, which substitutes the elasticity of the ballasted bed. To allow the vertical movements of the rail, the system is provided with a special tension clamp (see Figure 13). When additional stiffness is required, this system can include an additional steel plate and a lower high elastic baseplate, as shown in Figure 13. The intermediate plate allows obtaining additional vertical stiffness while limiting the stiffness of lateral tilting over of the rail.

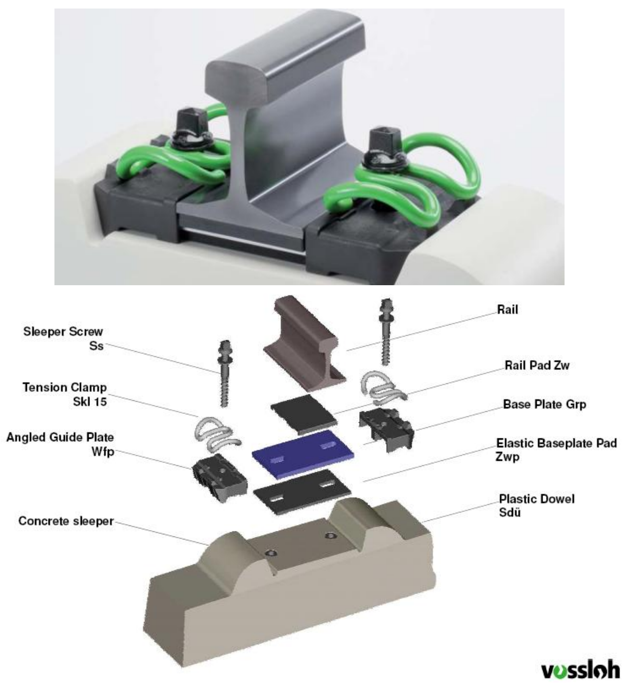


Figure 13.Vossloh Fastening System 300 with Skl 15 tension clamp for slab tracks [18]

Other slab track systems, such as Stedef or LVT, have more than one elastic level. When the lower elastic levels achieve a stiffness equivalent to the ballast and to an average subgrade, the rail fastening system can be a standard system for ballasted tracks.

As conclusion, the selection of the elastomers and, in particular, the adequate fastening system is a key factor in the design of the new slab track systems.

5.5 HIGH TRACK RESISTANCE

One of the main function of the infrastructure is to support the train. The railway wheels transmit vertical and horizontal forces onto the track. The strength of these forces is a function of the axle load, of changes in wheel loads when driving on curves or in case of unequal loading, of braking and starting, and the rolling of ovalized unbalanced wheels on a defective track. The permanent way has to distribute these forces in such a way, that the maximum admissible values for subsoil compression below the track and the admissible strains in the slab or ballast will not be exceeded.

5.5.1 TRACK RESISTANCE TO VERTICAL LOADS

Figure 14 shows the increase of wheelset loads in the course of railway history. It is remarkable how the wheelset loads for good wagons have steadily risen to today's value of 22,5 tons.

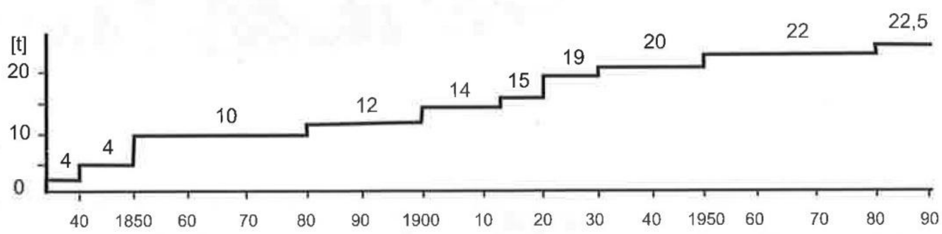


Figure 14. Chronological development of wheelset loads [3]

The track shall be designed to withstand at least the maximum axle load, the maximum dynamic wheel force and the maximum quasi static wheel force as defined in the respective TSIs. Table 9 summarizes the values stated in these regulations.

Table 9. Maximum vertical point loads

VERTICAL FORCES	HIGH SPEED	MIXED TRAFFIC
Maximum static axle load [7] [8]	17 t	25t
Maximum dynamic wheel force	170 kN (250 < V ≤ 300 km/h) 160 (250 < V ≤ 350 km/h)	-
Maximum quasi static wheel force	145 kN	-

Slab track lines, including bridges and earthworks, must be designed to support vertical distributed loads in accordance with the following load models, defined in EN 1991-2:2003 [19]:

- Load model LM71
- Load model SW/0, only for continuous bridges
- Load model SW/2,

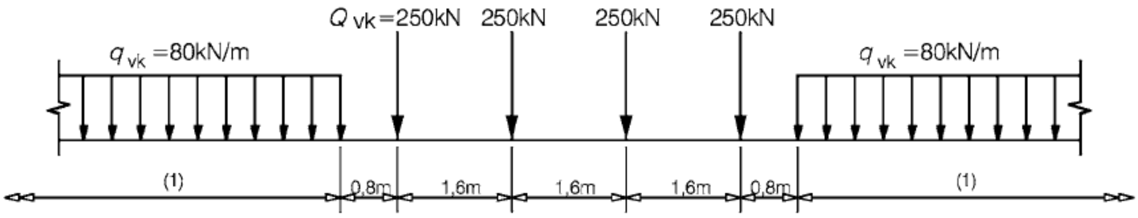
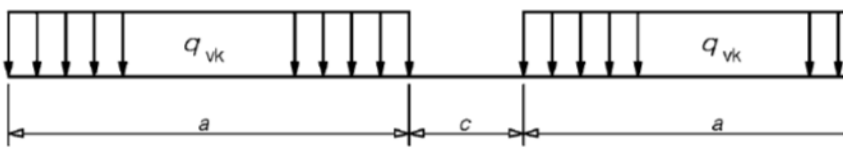


Figure 15. Load model LM71 and characteristics values for vertical loads [19]



q_{vk} = 133 KN/m
a = 15m
c =

Figure 16. Load model SW/0 and characteristics values for vertical loads [19]

The characteristics values given in Figure 15 and Figure 16 shall be multiplied by the factor alpha (α), which depends on the category of the line. Table 10 shows the minimum values of this factor according to the TSIs.

Table 10. Alpha factor for vertical loads on structures [7] [8]

	High speed	Mixed traffic
Category of the line	I	IV-M
Factor alpha (α)	≥ 1,00	≥ 1,10

5.5.2 Track resistance to longitudinal loads

The track shall be designed to withstand longitudinal forces arising from accelerating and braking of rolling stock, as well as thermal forces arising from temperature changes in the rail. Other longitudinal forces due to interaction between structures and track are out of the scope of this document and shall be taken into account as set out in EN 1991-2:2003.

According to [3], longitudinal forces arising as a consequence of braking may be up to 15% of axle load in electric engine vehicles, while two-axle goods wagons may be up to 25%. When braking is performed with a linear Eddy Current brake, the rails heat up and reduce the stability of the track. That is the reason why the TSI on rolling stock for HS lines [20] limits the acceleration or deceleration to $2{,}5 m/s^2$.

On the other hand, thermal forces can be calculated as follows:

$$\Delta\sigma = \alpha \cdot E \cdot \Delta T$$

where

Δσ rail stress (N/mm^2)

α coefficient of linear expansion of rail Steel ($11.5x10^{-6}$ 1//K)

E modulus of elasticity of the steel (215.000 N/mm^2)

ΔT temperature change (K)

Finally, the TSI on rolling stock for HS lines [20] states that emergency braking using this system shall not exceed 360kN per train.

Table 11 shows the maximum values when applying the simplification described above.

Table 11. Maximum longitudinal loads

Longitudinal forces	High speed	Mixed traffic
Traction and braking ($a \leq 2{,}5 m/s^2$)	25 kN per axle	60 kN per axle
Thermal forces (ΔT=35K, A=7687mm^2)	665 kN	
Emergency braking	360 kN per train	

For plain track the supporting structure is considered as continuously supported with enough contact area and no particular device is required for transmission of longitudinal forces due to passing trains. However particular design or devices are required when the continuity of supporting structure is stopped to limit the longitudinal displacement induced by thermal expansion.

5.5.3 TRACK RESISTANCE TO LATERAL LOADS

The track shall be designed to withstand with the maximum total dynamic lateral force exerted by a wheelset on the track due to lateral accelerations not compensated by track cant, which are defined by the High-Speed Rolling Stock TSI [20] as follows:

$$(\sum Y_{2m})_{lim} = 10 + (P/3) \text{ kN}$$

Vehicle curving causes guiding forces which stress the rails horizontally and at a right angle to the track axis. A force applied at an angle at the rail head is composed of a vertically acting part Q, a torsional moment M and a lateral guiding force Y. The guiding forces depend on several vehicle-specific technical parameters, such as axle load, wheelbase, bogie design, elastic and damping suspension parameters, but also on geometric conditions of the track and on speed.

The so called quasi static guiding force Y_{qst} is established by national rules all over Europe, although the following figure shows some approximated values depending on curve radius.

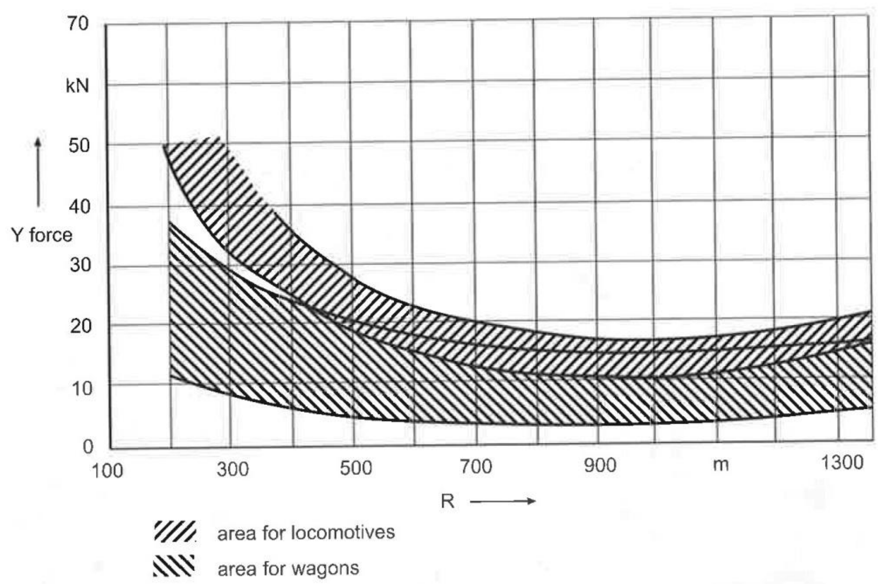


Figure 17. Horizontal guiding forces deending on curve radius [3]

According to previous references, Table 12 shows a range of values to be considered in the new designs.

Table 12. Maximum lateral loads

LATERAL FORCES	HIGH SPEED	MIXED TRAFFIC
Maximum dynamic lateral force	65 kN	91 kN
Quasi static guiding force	5-20 kN	10-50 kN

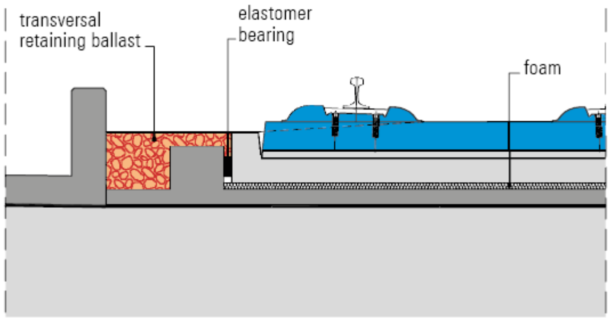
5.6 COMPATIBILITY WITH BRIDGE MOVEMENTS

Continuation of slab track across bridges could pose problems if certain typical mechanical behavior is not considered. A bridge provides a solid foundation for slab track, but temperature changes and traffic loading can cause longitudinal movements, bend of the spans and to twist over the supports. Hence the superstructure must be able to withstand these movements.

The following solutions can be implemented when slab track systems are applied in short bridges [2]:

- Fasteners with reduced clamping force: the movements of the bridge are compensated in the rail fastenings with reduced clamping force if the slab on top of the reinforced concrete roadbed is rigidly connected to the bridge deck or direct rail fastening systems are used.
- Embedded in bridge decks: in case of continuous rail-support rigidly connected to the bridge, maximum active extendable bridge-spans up to 15m are permitted. Larger spans are possible by applying extension devices and joints.
- Sliding slabs: the bridge structure can freely move underneath the slab track which "glides" on top. This option is limited to freely extendable bridge-spans up to 25m.
- Track frame on roadbed: the track lies freely movable on top of a concrete or asphalt-concrete roadbed. This solution exists due to possible motions and twisting of the sleepers on top of bridge-structures and spans up to 10m with frame spans limited to 25m.

There are several sliding slab solutions for short bridges. For instance, in simplified Rheda system a sliding mat and a 50mm layer of hard foam is fixed to the protection concrete of the structure with adhesive, so as to equalize as far as possible, the elastic and settlement behavior between the track on the structure and the adjacent slab track. In case of slab track with connected precast slabs, such as FF Bögl system, the slabs are laid on a 14cm minimum thickness profiled and reinforced supporting concrete slab from C30/37, itself laid on the sliding slab and the hard foam (see Figure 18). The profiled supporting concrete slab is manufactured in a trapezium cross-section so as to give the required superelevation in curved tracks.



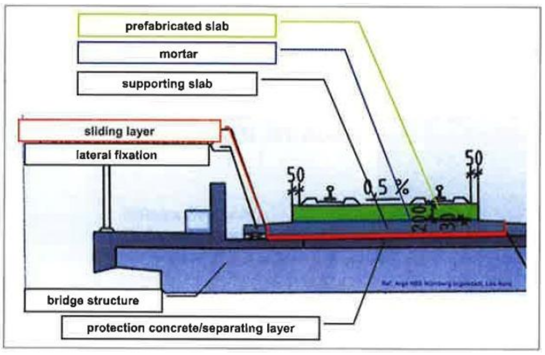


Figure 18. Typical layout of the slab track for a short bridge (left) and long bridge (right) [21] [22]

6 ENVIRONMENTAL REQUIREMENTS

6.1 POSSIBILITY TO INSTALL NOISE AND VIBRATIONS ABSORBERS

The Environmental Noise Directive 2002/49/EC [23] is the legal framework for the noise reduction in the European transport network. This Directive requires Member States to draw up "strategic noise maps" and action plans to reduce noise where necessary, but it does not set any limit value for noise emissions, which remains at the discretion of the national competent authorities. For instance, the German Federal Emission Regulation [24] requires in transport infrastructures noise levels below the values showed in Table 13.

Table 13. German maximum environmental noise levels for new built or modified transportation infrastructures

PLACE	DAY	NIGHT
Near hospitals, schools, sanatoriums	57 dB(A)	47 dB(A)
Pure residential areas and small colonies	59 dB(A)	49 dB(A)
In central areas, villages or mixed areas	64 dB(A)	54 dB(A)
In industrial areas	69 dB(A)	59 dB(A)

The noise in railways operation mainly arise from the wheel/rail contact area. In particular, there are two different sources [3]:

- Airborne noise, due to engine, rolling, curves, braking and aerodynamic noise.
- Vibration and, as a consequence, structure-borne noise.

The increase in train speeds, axle loads, and traffic volumes on current train lines has also led to increases in the noise and vibration to which the surroundings are subjected. Irregularities between rail and wheels, as well as the dynamic deformation of tracks when rolling stock passes, introduce vibrations into the subgrade. These vibrations are propagated into adjoining building structures, which vibrate to lesser or greater degree. Secondary airborne noise can likewise produce disturbances.

The TSI Noise [25] defines the maximum noise levels for stationary and pass-bay noise of rolling stock on defined rail reference tracks and defined speed. There are no specific limits for trackside noise, although the reference value is the traditional ballasted track with wooden sleepers. Referring to this basic value, the noise radiation of slab track area about

+5dB [3], so mitigation measures in this type of infrastructures have to be considered in the design.

Depending on the main source of noise, there are different solutions to minimize the noise emission and transmission. Of course, the elastomers described in 0 for increasing track stiffness also collaborate to this goal. The following sub-chapters show other noise mitigation measures to be considered in the new track designs.

6.1.1 AIRBORNE NOISE

The dominant sound sources are the propelling forces of the vehicles up to a speed of about 40km/h, the rolling sound between 40 and 250km/h and the aerodynamic sound over 250km/h. So the rolling sound is the most important for the greatest proportion of traffic.

It is essential to understand that the coarse surface of the wheels is as important as the coarse surface of the rails. Furthermore, the developing rolling noise linearly depends on the running speed.

A lot of good solutions have been developed in the last decades for mitigating rolling noise emissions. The increasing the quality of the rail surface by grinding or planning is a good solution to keep the emitted noise due to rail coarseness below control. The use of compound blocks in good trains instead of grey cast iron brake blocks also contribute reduction of noise associated to coarseness of wheels. Other example, the oil lubrication of rail in sharp curves is targeted to reduce wear but also have a great impact on reduction of screeching noise.

When these countermeasures are not enough, it is required to put in place track side noise absorber barriers. In order to increase their effectiveness, these barriers should be as closer as possible to the source of noise, that is, to the rail. To this end, the noise barriers could be a part of the slab track system or, at least, it should be take into account the possible physical disturbances between the systems.

Furthermore, the surface structure also has an impact on airborne noise absorption. A closed structure such as slab tracks has in general not the same absorption as an open structure like the ballasted track. The harsh sound of the slab track is slightly higher (about 2-5 dB) than the one of the noise absorbing, porous ballasted track.

This problem can be overcome by installing acoustic concrete as a finishing layer on the concrete slab. In the case of tramways and inner-city railways, slab track also enables the use of a grass-covered track system offering ecological and noise reduction advantages. Other systems, such as FF Bögle or OBB Pörr have developed special prefabricated sound absorbing elements that can be put between and outside the rails and protected against withdrawing forces (see Figure 19). This way, noise emission can be reduced up to 2-3 dB.

Figure 19. Left: Artificial Grass Track, CDM [26]. Right: Absorbing elements, FF Bögl [10].

The continuous embedded and supported rail systems have a rubber pack surrounding the rail to support it and to prevent water penetration, which also collaborate to the vibration damping.

Finally, other measures have been locally implemented in slab track systems such as attenuation of the rail web by special damping systems or additional support points between two neighbouring rail fasteners, which achieve important reduction of airborne and structure-borne nuisance (see Figure 20)

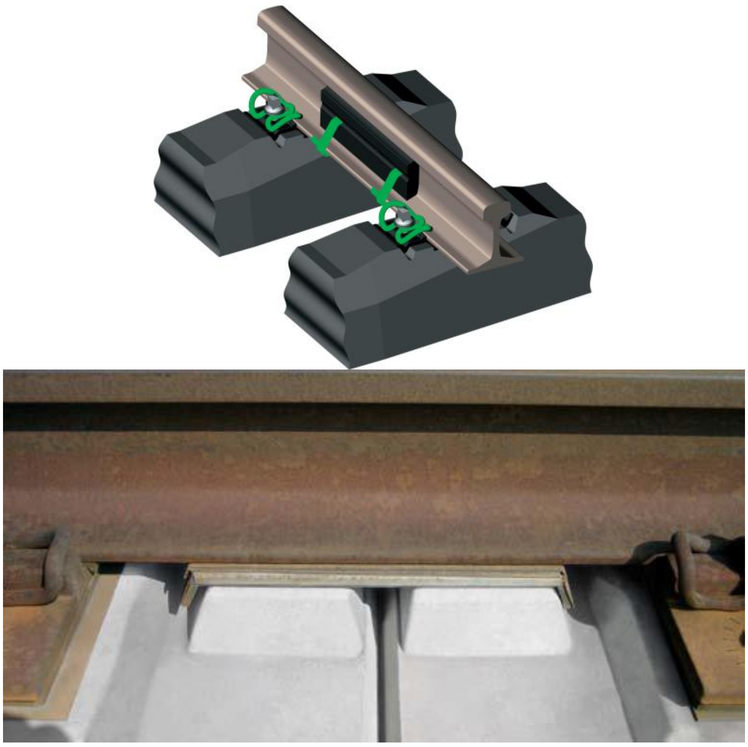


Figure 20. Left: Rail web damping system, Vossloh FS [27]. Right: FF Bögl additional support points [10]

6.1.2 Vibrations and structure-borne noise

Compared with ballasted track, vibrations and structure-borne noise in are distinctly increased in slab track. The reason is the uncoupling of the rail by the elastic rail fastening and the lack of noise-absorption of the loosely bound ballast bed.

Slab track systems may be designed to offer improved vibration attenuation by the interposition of elastomeric layers within the rigid track structures. These systems then approximate mass-spring systems.

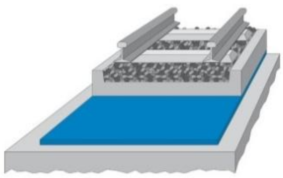
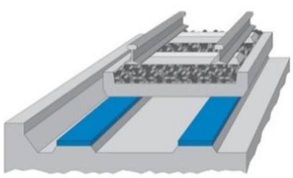
The characteristics of the amplification function of single mass oscillators play a key role in the design of mass-spring systems. Mass-spring systems can be implemented in light, medium-heavy, or heavy models. Light mass-spring systems are mounted on either strip supports or entire-surface supports made of elastomer matting. For heavy mass-spring systems, individual supports in the form of elastomer blocks or steel springs are employed. The deeper the frequency of the vibration to be reduced, the higher the required mass of the track concrete layer [28].

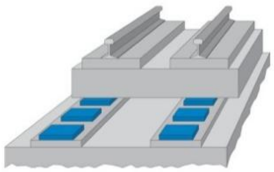
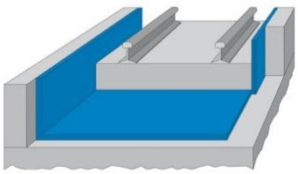
The ability to combine elastic elements in the track structure, as described in section 0, with elastomer matting below the slab is one of the main advantages of slab track systems. It allows designing up to 3 elastic level systems, namely high attenuation systems, which could be used in high sensitive environments.

In the selection process of the appropriated elastic support to design the mass-spring systems it is important to take into account the construction procedure of the slab track system.

Table 14 shows the main types of elastic supports and their characteristics.

Table 14. Elastic support for mass-spring systems [29]

Mass-spring system	Description
Full-surface support for floating slab 	Depending on the specific application, a full-surface elastic support achieves natural frequencies in the range of 14-25Hz. This corresponds to an achievable structure-borne noise damping of up to 30dB in the supercritical frequency range.
Linear support for floating slab 	Linear supports are preferred in mass-spring systems that make use of prefabricated elements or combine prefab with in-situ casted concrete. The horizontal forces that arise both in the direction of travel (braking and acceleration forces) as well as perpendicular to the track axis (e.g. centrifugal forces, side forces resulting from track geometry errors) can be handled well by relatively large support surfaces. With linear support, it is possible to achieve lower support

MASS-SPRING SYSTEM	DESCRIPTION
	structures natural frequencies (8-15 Hz) than with full-surface support while keeping expenses reasonable. Overall, linear support achieves a higher damping of structure-borne sound.
Point-like support for floating slabs 	The selected construction method for the track support slabs or track troughs determines the type of point-like support. Generally it is used with track support slabs created using site-mixed concrete and lifted into place after hardening. The supports are inserted through openings in the plate. The lowest natural frequencies are achievable with point-like supports (5-12Hz). This type of support satisfies the highest requirements for structure-borne sound protection. Structure-borne sound damping of 30dB and more can be achieved with this type of system.
Light mass-spring system 	This solution is a variant of full-surface support that is primarily used for tram lines. In this system, base and side wall mats completely decouple the track bed from its surrounding environment with regard to vibrations. With this system, natural frequencies from 15 to 22Hz can be covered, allowing for structure-borne noise isolation of up to 20dB in the critical frequency range.

The following requirements may apply to elastic supports designed for mass-spring systems:

- Simple, fast and inexpensive construction methods
- Low risk of construction errors
- Wide-area load distribution in the subsoil
- Damping of structural vibration of track support elements
- Low number of installation joints
- High horizontal stability of the entire system
- High efficiency and long-term stability
- Minimal maintenance expenses
- Economy of the entire system

6.1.3 Maintenance noise

The noisiest activity in railways is not the train passing, but the track maintenance, which is usually done at night when the allowed noise limits are lower. Some manufacturers of maintenance machines have develop specific solutions to limit the sound pressure levels (See Figure 21).

Figure 21. Soundproof panels to reduce tamping noise. Matisa [30]

Due to the low maintenance needs or slab track, there will not be many nightly maintenance works disturbing the nearby residents. Nevertheless, in case that some innovative track design requires new maintenance methods, the noise level of the required machinery should be also taken into account.

6.2 Use of waste materials

The Waste Framework Directive 2008 establishes the legislative framework for the management, recovery and disposal of waste [31]. This regulation sets concrete objectives for the reduction of specific forms of waste by the year 2020. The recycling targets are currently under review due to important implementation gaps amongst Member States [32].

The construction and renewal of railway infrastructure has an enormous potential in terms of the use of waste, including that deriving from its own activities and from other sectors. The use in track construction of materials made from recycled waste enables, on the one hand, a reduction in the demand of non-renewable natural resources, and on the other, a reduction in the amount of waste dumped without being used.

Some research projects have recently developed and tested recycled components for railway track. For example, ECOTRACK demonstrated the technical and market viability of a railway profile for continuous embedded rail systems made with recycled rubber from end-of-life tyres [33]. LIFE GAIN studied the use of steel furnace slag as recycled aggregate to form sub-ballast and subgrade track foundation layers [34]. The project RECYTRACK demonstrated the environmental benefits and economic viability of recycled rubber from end-of-life tyres for use in insulated blocks and elastomeric mats for ballasted and slab track systems [35].

The use of waste materials in the new slab track systems shall be also considered in the design. Apart from the clear environmental benefits, it is important to assess the technical and economical impacts.

6.3 NON-CONTAMINANT LEACHATE

The use of innovative materials in railway tracks could lead to important technical improvements in the designs, while keeping the cost at reasonable level. Other industries such as aeronautics, road vehicles, even rail vehicles, already make use of composite, graphene, titanium, etc. When using these materials in transport infrastructure, the components are in contact with the soil and groundwater, so it became important to assess the possible environmental impact not only after disposal but also during exploitation as a leachate.

Leachate is a widely used term in the environmental sciences where it has the specific meaning of a liquid that has dissolved or entrained environmentally harmful substances which may then enter the environment.

The most used method to investigate the contaminant ability of a solid material, namely the accessibility to the medium, is the leaching test laboratory. Although it should be noted that sometimes the results are not entirely transferable to their behaviour in the natural environment can be considered as a valid study.

Both the US and Europe have conducted several methodologies for laboratory testing in order to determine what characteristics would have the leachate generated by the use of building materials in road and rail projects, as well as the effects of this leachate both in the soil and groundwater, focusing mainly on the analysis of organic compounds and metals. The most common test in Europe to extract the leachate from a solid is the standard EN 12457 "Characterization of waste. Leaching. Compliance test for leaching of granular waste materials and sludges [...]” [36].

7 CONSTRUCTION REQUIREMENTS

7.1 LOW NUMBER OF CONSTRUCTION STEPS

Construction of slab track systems also differs as a result of the different design features. These differences are relevant both to the evaluation of the functionality and durability and to the profitability. In particular, the type and number of work steps of building trades required for construction of the individual components, as well as the necessary standard or even special equipment have an effect on cost, construction time and susceptibility of a system to weather influences and potential deficiencies during execution of work. Apart from the labour and material required, each work step and each trade more or less involves a risk of defective work or quality losses due to unfavourable boundary conditions (e.g. weather). In other words: The simpler or less sensitive the design of a slab track, the easier its construction and he more reliably and cost-effectively a high quality standard can be achieved [37].

As a general rule, the more the in-situ works, the more the construction steps required. The following examples illustrate the differences among the most usual slab track systems [37]:

- Sleepers embedded in concrete, such as Rheda, requires 30 construction steps
- Sleepers on top of asphalt/concrete layers, such as BTD, requires 14 construction steps
- Direct support on monolithic in-situ slabs, such as BES, requires 10 construction steps

However, optimised construction procedures can be developed from the design phase, achieving important reductions in the number of construction steps and increasing the overall construction performance. For example, during the construction of the HSL Zuid (The Netherlands), the Rheda 2000 system was built in 18 work steps (see Figure 22), which is a high reduction from the 30 steps required in previous versions [38].

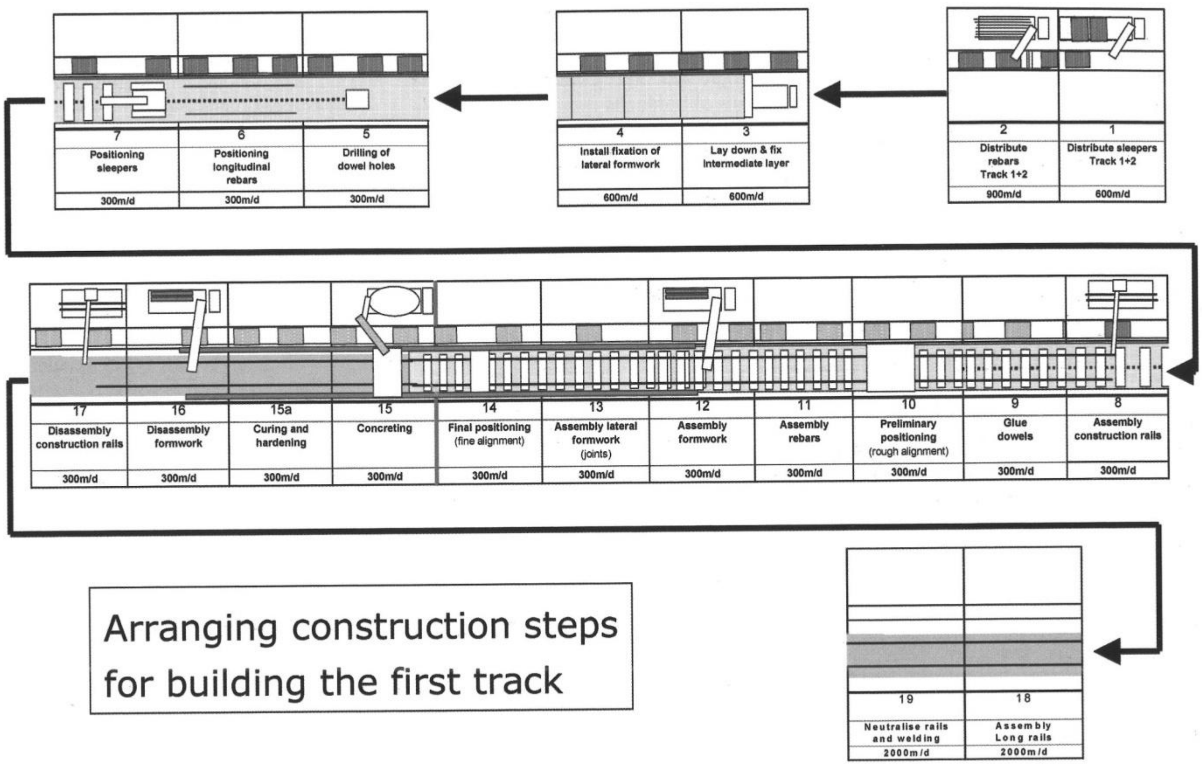


Figure 22. individual steps of the construction process for Rheda 2000 system in the HSL Zuid [38]

7.2 FAST CONSTRUCTION

The construction performance of a slab track system depends on the number of in-situ works, including the assembly of precast elements and the track alignment. There is always a critical step which determines the overall construction performance. For example, the construction of the base layer at the HSL Zuid had a construction performance of 600m/day, but the backbone was the positioning and concreting of the track frame, which was 300m/day [38].

The manufacturing of precast elements can also limit the construction performance. For example, Table 15 shows the performance on every construction step in the the J-Slab (Shinkansen) slab track system. It can be observed that the fast procedure double the performance in every step except the manufacturing, which is the bottleneck of the method.

Table 15. Construction speed of Shinkansen slab track [39]

WORKS	STANDARD PROCEDURE	FAST PROCEDURE	
	PERFORMANCE (M/DAY)	PERFORMANCE (M/DAY)	METHOD
Slab manufacturing	200	300	Addition of formworks
Temporary rail laying	800	1600	2-parties
Slab carrying and laying	200	400	Using double track
Slab adjustment	200	400	2-parties
CA mortar injection	250	500	24-hours work

But the problem of low performance on manufacturing precast elements could be avoided if the slab can be stacked and stored in advance. As an example, the construction performance in the HS line Nuremberg-Ingolstadt using the FF Bögl slab track system was about 28 slabs placed per day and the production rate at the factory was not the bottleneck thanks to the intermediate storage of slabs, as shown in Figure 23 [10]. The ability of the prefabricated elements to be stacked is considered a design requirement for this kind of slab track systems.

Figure 23. Storage of FF Bögl precast slabs [40]

Figure 24 shows the construction performance of the most common slab track systems. The most effective ones achieve more than 300 metres/day, which is a design requirement for new slab track systems in order to be competitive enough.

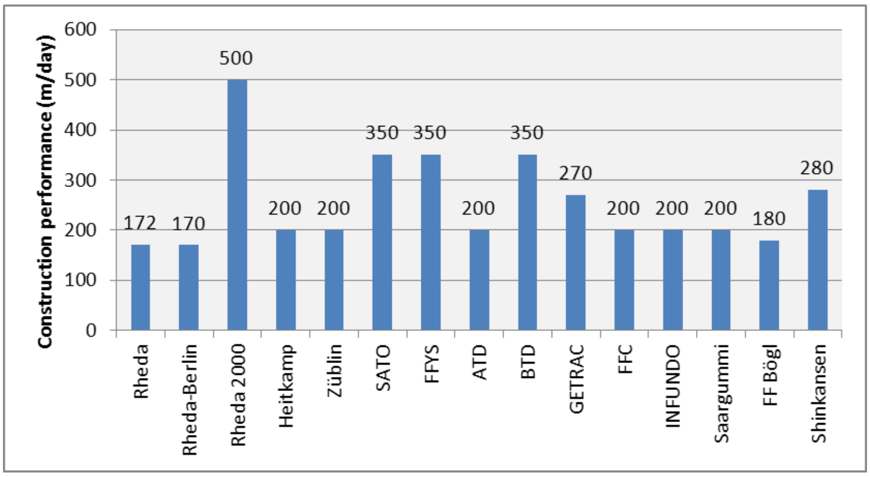


Figure 24. Construction performance on different slab track systems [3] [4] [10]

Apart from the Rheda 2000 system, which construction is highly mechanized thanks to many years of improvement, slab track systems founded on asphalt layers achieve high construction productivity because asphalt does not require hardening and can be subjected to loading immediately after cooling.

In this sense, it should be take into account that concrete base layers can be loaded only after the hardening process, when it has achieved a minimum resistance to pressure of 12 N/mm2, which is usually achieved after 3-7 days, while asphalt layer takes no more than 2 or 3 hours to cold down below 50ºC and reach enough resistance.

7.3 Modularity

Modularity is the degree to which a system's components may be separated and recombined. In construction, it means that modules are a bundle of redundant components that are produced en masse prior to installation.

Besides reduction in cost and flexibility in design, the use of standardised construction elements allows a high degree of prefabrication (independent of building site impacts) and therefore extensive assembly works and assembly quality.

Furthermore modularity offers other benefits during the service life of the system such as adaptability to changing traffic demands. The system can be upgraded just by plugging new improved modules. On the other hand, a drawback of modularity is that modular systems are not usually optimized for performance. That is probably the main challenge for designers of modular systems.

Prefabricated track systems, such as FF Bögl, ÖBB Porr and Shinkansen have successfully applied an approach to modularity to the precast concrete slabs, where the following advantages have been widely demonstrated:

- High level of mechanisation possible.
- Labour-saving construction at site.
- The rail can be directly adjusted and fixed.
- Less immune to falling workmanship.
- Repair and renovation friendly.

However, in case of structural defects, settlements or upgrading needs the slabs have to be replaced as a whole, as described in section 8.2. The modular track systems shall allow the replacement of isolated components, which could be enabled by elastic elements placed between precast items, as shown in Figure 25.

Figure 25. Elastic components between precast concrete elements allow modularity. CDM-BSP track system [41]

According to this requirement, it is desirable that new developed track systems allow, as much as possible, the replacement of individual components to allow easy repair procedures and upgrading methods.

7.4 EASY TRANSPORT OF PRECAST ELEMENTS TO CONSTRUCTION SITE

In case of prefabricated slab track, the size and total weight of individual slabs are important for the construction phase (transport and installation), and also for the removal and replacement if necessary during maintenance operation.

Trucks are able to transport up to 30tn through most of European road network, while the trailer usually have a 12m long and 2,60m width area for placing cargo. Higher weights and dimensions are possible but the road authority shall give a special authorization, which usually takes a long time on administrative procedures. Table 16 shows the size and weight per slab of several prefabricated slab track systems.

Table 16. Size and weight of prefabricated slab track [10] [2] [3] [4] [1]

SLAB TRACK SYSTEM	LONG (M)	WIDTH (M)	THICK (M)	WEIGHT (TN)
FF Bögl **(version 1)**	6.45	2.55	0.20	9.0
FF Bögl **(version 2)**	6.45	2.80	0.20	10.0*
ÖBB-Porr	5.16	2.40	0.24	8.0*
ÖBB-P**orr (tunnel)**	5.16	2.40	0.16	5.2
Shinkansen (1972)	4.95	2.34	0.19	6.0*
Shinkansen (1972-tunnel)	4.95	2.34	0.16	5.0
Shinkansen (1997)	4.90	2.22	0.22	6.5*
Shinkansen (1997-tunnel)	4.90	2.22	0.19	5.6*
IPA (1984)	4.75	2.50	0.18	5.8*
Railtech (floating sla**b)**	3.70	2.24	0.18*	4.0
FST (floating slab)	1.25	2.85	0.19	1.8*

* Estimated values.

Most of previous listed slab track systems can be moved by road, but no more than 3 to 6 slabs at a once. For instance, FF Bögl slabs, with a weight about 9 tonnes, can be carried on a highway lorry only three per delivery, as shown in Figure 26. In order to be competitive with existing slab track systems, the new designed elements shall be also transportable by road, according to the weight and size limits above mentioned.

Figure 26. Transportation and rough placing of precast slabs [40]

7.5 EASY ALIGNMENT OF TRACK PANELS

Common to most of slab track construction procedures is the costly and time consuming process required for the correct positioning of the precast elements. This precise installation is essential for good long-term stability of a slab track system. Geometric imperfections during the installation stage must be avoided by using techniques adopted for road pavement construction for the track structure and the formation work, coupled with a precise dimensional control of the actual construction process.

There are two different approaches for the construction of slab track systems:

- Top-Down construction procedure: Used by Rheda 2000 and LVT, among others. This building method consist of fitting together rails, fastening systems and sleepers or blocks to constitute a frame whose geometry is adjusted by a temporary wedging system, before pouring a concrete or mortar between the supporting structure and the blocks or sleepers. By this way, this method avoids adding up of the components' production tolerances. It guarantees excellent track geometry by placing the track in its end position prior to pouring concrete.
- Bottop-Up construction procedure: Used by Zublin, GETRAC and ATD among others. Several layers of supporting structure are installed while improving the geometrical precision before laying sleepers above them. These layers can be asphalt or concrete. The major problem is that manufacturing process of prefabricated slabs or sleepers do not allow easily to obtain the required geometrical precision for high speed.

A possible intermediate approach consists in preassembling plates without anchors on rails, to get the desired rail geometry, to drill holes through the plates, to put in place the anchors with chemical sealing and to adjust the plate vertically with a mortar [4]. This is the method used by slab track systems based on large precast concrete slabs, such as FF Bögl, OBB Pörr or J-Slab (Shinkansen).

As mentioned above, in botton-up construction procedures the bearing layers shall be produced very exactly to reduce the needs for vertical adjustment, which is quite limited in spite of state-of-the-art adjustable fastening systems (see section 0). Most of the slab track manufacturers recommend small tolerances on the levelling of supporting layers. Table 17 shows a summary of these requirements.

Table 17. Usual geometric requirements on supporting layers [3]

LAYER	TYPICAL THICKNESS	ACCURACY REQUIRED ON TOP OF THE LAYER
Concrete bearing layer	200mm	±2mm
Asphalt bearing layer	300mm	±2mm
Hydraulically bounded bearing layer	300 mm	±10mm
Frost protective layer	500-700mm	±20mm

Exceptionally precise setting-out methods are required when constructing individual rail support systems, such as the one installed at the experimental track at Waghäusl (DB AG), consisting of continuous supported rail EDILON-INFUNDO for high-speed rail service. This experience shows that even with the use of specially adapted slip form pavers, additional manual works are needed to form the surface of the concrete slab sufficiently so that the rail supports are precisely located [21].

The installation procedure and alignment method shall be key factor in the design of the track system in order to achieve the required track quality with a good construction performance.

For instance, the Rheda Classic system use spreader bars and spindle-base adjustment units, which enable precise alignment and securing of the track panel before pouring the contact mortar. The spreader-bar adjustment system involves a combined technique consisting of spindles and spreader bars which allow both vertical and horizontal track-panel alignment (see Figure 27).

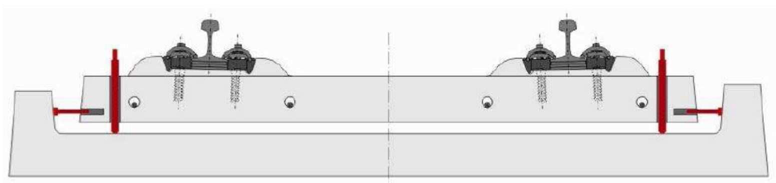


Figure 27. Rheda classic system. Spindles for the alignment of the track panel.

The Rheda 2000 system, following best practices in previous versions, also includes an adjustment system by spindle brackets, as shown in Figure 28. This system made possible to allow height tolerances up to +5/-15mmin the cement treated base, similar to roadway construction standards. This system was used, for instance, in the new high-speed line Nuremberg-Ingolstadt put into service in 2006 [21].

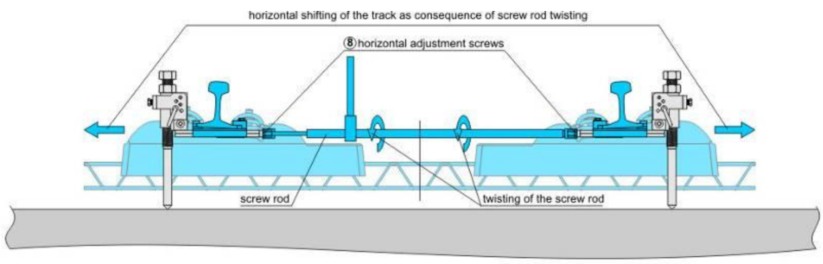


Figure 28. Rheda 2000 system. Spindle brackets for alingment of the track panel.

8 MAINTENANCE REQUIREMENTS

8.1 LOW MAINTENANCE

The low maintenance needs is one of the common features of slab track systems and should be also shared by the new developed ones.

Given the high bearing capacity of the supporting layers, deviations of the track alignment are small and unlikely to occur. The condition of the track geometry is, therefore, very good in slab track systems and will remain likewise, keeping track quality and passenger comfort without the need of intensive maintenance activities.

Only regular rail grinding, replacement of the rails after their lifespan and elimination of vegetation at the margins of the slab track are required, in principle with the same frequency as in ballasted track.

8.2 EASY REPLACEMENT OF AGED OR WORN TRACK COMPONENTS

Due to the long life of slab track systems, it is expected to replace at least one time the track components subjected to the highest stresses, i.e. rails, fasteners and elastomers, so the procedure to exchange this elements shall be considered in the design phase.

For instance, rails are subjected to [4]:

- The fatigue as all metal working cyclically.
- The wear by wheel contact (possibly accelerated by grinding operations).
- Repair activities on punctual defects or breaking, notably welding.

The utilisation of traditional fastening systems allow to replace rails with the minimum disturbance to traffic operation, thanks to well-known, even automated maintenance procedures. This possibility disappears in case of embedded rails systems, which oblige to partially reconstruct the system and carry out a new track alignment.

On the other hand, elastomers suffer from ageing linked to the damping and the high level of solicitation existing in the proximity of the rail. Rail pads, baseplate pads and sleeper pads should be replaceable in easy conditions because their service life cannot be demonstrated on periods about 40 to 60 years. The same applies to lateral stops on fastening systems, which ensure the gauge and the transverse effort transmission [4].

In systems with rubber booted sleepers such as GERTRACK or ATD, sleepers remain as replaceable components. Precast slabs can also be replaceable, but in this case the replacement procedure shall be defined from the design phase by manufacturers. For example, Figure 29 shows the replacement procedure defined by ÖBB Porr. The two tapered grouting openings which prevent a lift off of the track base plate, can be cut fee or chiselled out and the slabs can be replaced separately within three to four hours [42].

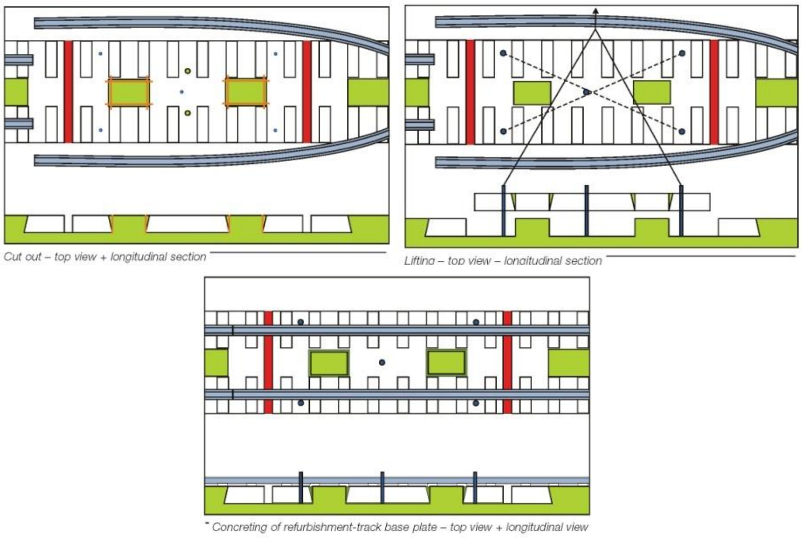


Figure 29. Replacement procedure for OBB Porr slab track base plae

In case of monolithic systems, sleepers are used only for alignment purposes and after that they are embedded in in-situ concrete, being no longer separable from the support slab. In this case, the repair is longer and more expensive.

The modularity described in section 7.3 will contribute to the fulfilment of this requirement.

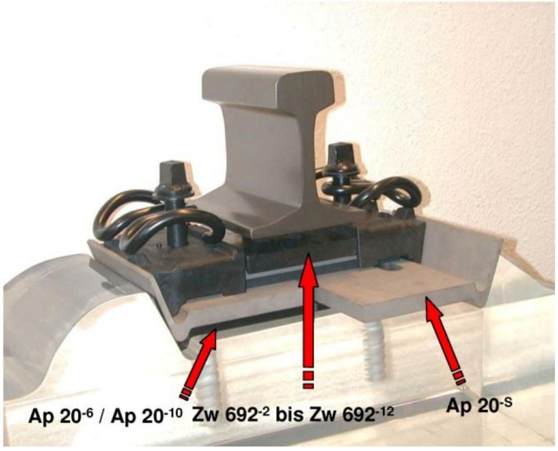
8.3 FRIENDLY REPAIR PROCEDURES ON UNFORESEEABLE EVENTS

Repair works for the slab track use to be complicated, cost-intensive and time-consuming. The operation hindrance cost in case of long closures of slab track lines due to unexpected defects are extremely high and can hardly be calculated or predicted today.

At the moment there are only very expensive repair methods to apply after serious damages, such as a derailment, large residual settlements, etc. Curing and hardening of concrete takes a long period of time. This means that a serious accident in a slab track based system leads to a total closure of the line and to long operational hindrances.

For example, a settlement defect of 20mm occurred at the high-speed line Berlin-Hannover (Germany) made necessary to temporarily restrict speed to 70km/h. The repair works were carried out during expensive night shifts [3].

Adjustable fastening systems offer a real, although limited, solution to small settlements. The most important manufacturers of rail fastenings have developed special systems for slab track able to adjust lateral and vertical position with easy and fast procedures. For instance, the Vossloh FS300 allows the adjustment of vertical position up to +76mm by interposition of additional steel plates due to the length reserve of anchors to the concrete slab (see Figure 30 left). The lateral adjustment is also possible by systems of eccentrics on the fixing of the intermediate plate. The Pandrol VIPA SP also offers a solution to face both vertical and lateral adjustment as can be sawn in Figure 30 right.



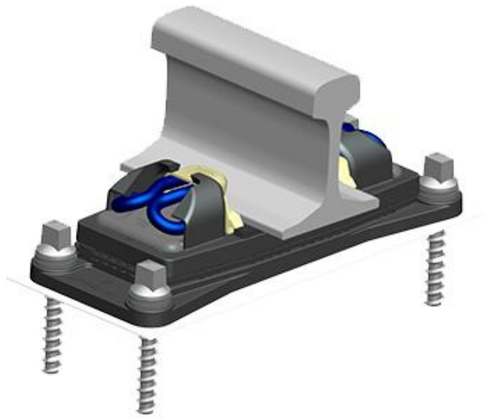


Figure 30. Adjustmente of fastening systems. Left side: Vossloh FS300 [18]. Right side: Pandrol VIPA SP [43]

In case of precast slab systems, it is also possible to move the whole slab if larger settlements, unable to be compensated with the rail fastenings, occur. For example, FF Bögl plates integrate spindles (see Figure 31) able to carry out vertical readjustment just by separating the slab from the sealing material by a cable saw. The developing cavity is then sealed again with bitumen cement mortar.

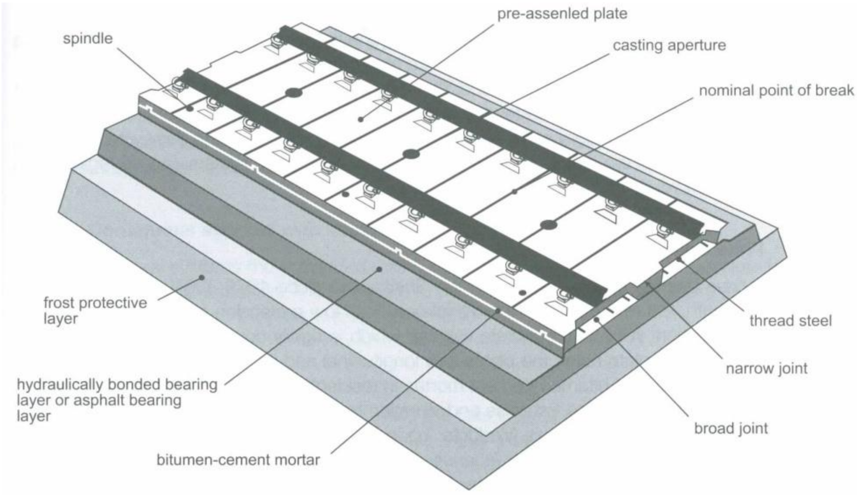


Figure 31. FF Bögl slab track system [3]

In addition to settlements, derailments is the source that could derive into hard maintenance tasks in slab track systems. For instance, the derailment of the Toki 325 bullet train on the Akita-Shikansen line (Japan) due to the Niigata Chuetsu Earthquake occurred in 2004, required just the replacing of fasteners and rails in the derailment area, what was a relatively fast repair action, but the repair of damaged of slab tracks in the Uonuma and Myoken tunnels took more than two months. About 300 concrete slabs had to be lift, removed from the tunnel, repair the concrete base and slabs and bring the slabs back in four or five at a time and realign them [44].

In order to overcome these unlikely, but costly, maintenance tasks, the new track system shall be based on modular concepts, which is a requirement further described in section 7.3.

9 OPERATIONAL/SAFETY REQUIREMENTS

9.1 PERFORMANCE PARAMETERS

The Technical Specifications for Interoperability (TSI) relating to the infrastructure subsystem of the trans-European high-speed and conventional rail systems [7] [8], set functional requirements to be met by the infrastructure subsystem depending on the "category" of the line". For the purpose of the TSIs the European railway transport network may be subdivided into the following categories:

Table 18. TSI Line categories

Lines	Categories
High-speed lines	Category I: New lines for speeds of at least 250 km/h Category II: Upgraded lines for speeds of the order of 200 km/h Category III: New or upgraded lines with special features and adapted speed
Conventional rail lines	Category IV: New core TEN lines Category V: Upgraded core TEN lines Category VI: New other TEN lines Category VII: Upgraded other TEN lines

The conventional rail lines are in turn subdivided into different types of traffic, which is represented with a suffix: Passenger traffic (-P), freight traffic (-F) and mixed traffic (-M).

The Capacity4Rail is focused on the core TEN lines and the new slab track systems will be developed for high-speed and mixed traffic, so the categories of lines to be applied are Category I and Category IV-M respectively, which are characterized by performance parameters shown in Table 19.

Table 19. TSI Performance parameters

	HIGH SPEED	MIXED TRAFFIC
Category	Category I	Category IV-M
Traffic	Passenger	Passenger+Freight
Axle load	17 t	25 t
Line speed	250-350 km/h	200 km/h
Train length	400 m	750 m
Gauge	GC	GC

9.2 COMPATIBILITY WITH LINEAR EDDY CURRENT BRAKES

The eddy current brake is mainly used in the entrance area of railway stations and only very rarely on open lines. This braking system is usually installed in the new generation of high speed trains and it offers the advantage of lower wear of the brake elements of the rolling stock, but its stray fields influence traditional signalling equipment and railway infrastructure.

When a linear eddy current is applied, the rails are heated up and therefore, could diminish track stability. The average rise of rail temperature in typical conditions is approximately 16 ºC, but can amount to up to 25 ºC under extreme operational conditions. In these circumstances and under strong insulation the rail temperatures can rise to over 80ºC and cause additional rail tension due to which the "critical temperature" might be exceeded [3].

The high track stability inherent to slab track systems ensure a good behaviour under eddy current braking systems, so no special countermeasures are envisaged to fulfil this requirement.

9.3 TRACK ACCESSIBILITY TO ROAD VEHICLES

Considering the evacuation of passengers following an incident, it is important to eliminate tripping hazards on the ground. Rescue vehicles are expected to get access to the location of the incident, as well as extinguishing resources in case of fire. As stated in the specific TSI 'safety in railway tunnels' [45], the infrastructure facilities shall guarantee the self-rescue evacuation routes as well as the access for rescue services.

Maintenance interventions are also more complicated in tunnels than in the open air. The access of vehicles using tires in addition to dedicated rail-road vehicles, simplifies the execution of maintenance works.

Figure 32. Accessibility of tunnel for road vehicles [46]

In principle, road vehicles can drive on the slab track in tunnels more easily than in ballasted track (see Figure 32). The geometric design of some slab track systems, such as LVT, already have obstructions-free centre that guarantees a good access for road vehicles. Other track systems, such as FF Bögl, uses a prefabricated element installed on the slab track between the rails to facilitate track accessibility. There are also generic devices in the market which offers both derailment protection, sound-absorption and a drivable surface for road vehicles. (see Figure 33).

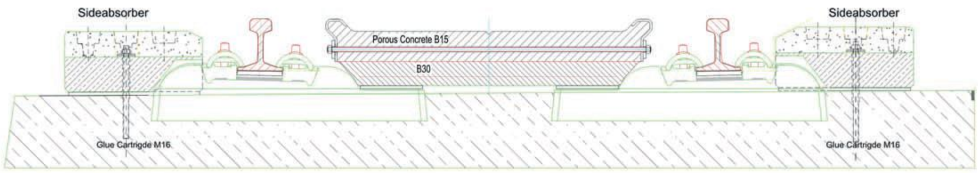


Figure 33. BAFS System with side absorption units on slab track [47]

9.4 Integration of/compatibility with derailment protection devices

Antiderailment devices are usually required in safety critical sections by most of railway administrators. For instance, the Specification for the Construction of Slab Track, issued by DB-AG, requires that track in twin-track tunnels shall be fitted with derailment retention arrangement, namely ‘guard rails’, so that lateral displacement of bogies or wheelsets is limited in the event of derailment, preventing secondary derailment of further wheelsets.

The usual arrangement of derailment retention device consists of an auxiliary rail fixed 180 mm outside the outer running rail on a special baseplate with two rail positions, but the elastic rail support points used in slab track make this arrangement unsuitable. Special fixing points need to be located either on the sleepers or in the spaces between the sleepers. One solution provides the special UIC33 rail section (designed for check rails) on mountings on the sleepers; this arrangement was adopted on two bridges on the new high speed route Hanover–Berlin [47].

Most of commercial slab track systems offer alternative solutions to protect derailment based on additional devices to be installed after construction. For example, FF Bögl uses prefabricated blocks fixed by dowels between the rails (see Figure 34). OBB Pörr has develop a guardrail anchored to the slab and fully compatible with the reinforcement inside the concrete plate (see Figure 35).

Figure 34. FF Bögl slab track system. Derailment protection device.

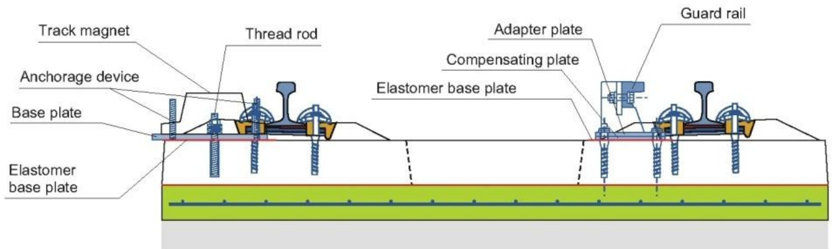


Figure 35. ÖBB Porr slab track system. Derailment protection device.

The new slab track systems shall allow either the fixing of the auxiliary rail (standard solution) or be provided with integrated derailment protection devices.

9.5 Electromagnetic compatibility

Slab tracks, with their reinforced concrete layers, have substantial electromagnetic properties. In their development, it is necessary to consider effective measures against lightning and catenary line breakage. These measures involve grounding elements (equipotential bonding). Modifications or extensions necessitate regular inspection of these elements. In high-speed rail traffic, unrestricted compatibility is absolutely essential between train control systems and the slab track. Control systems operate with transmission systems and use electromagnetic signal transmitters and/or signal receivers. These control systems function directly in the reinforced-concrete track layers themselves (e.g., LZB and ETCS), or in the direct vicinity of these layers (e.g., UM 71 etc.). It is crucial to study the effects of longitudinal reinforcement, since it represents the primary attenuating element [28].

10 COST REQUIREMENTS

10.1 LOW CONSTRUCTION COST

The construction cost of a slab track system in plain lines consists of manufacturing of precast elements, delivery, assembly and installation of complementary equipment, such as noise absorbers or derailment devices. Table 20 shows the total construction cost found in the literature for several slab track systems, compared with traditional ballasted costs. It should be noted that this cost does not include the impact on other civil works, such as:

- Earthworks: 1,5 to 3 times more expensive
- Bridges: 1,3 to 2 times more expensive
- Tunnels: 1,1 to 1,5 times more expensive

On the other hand, the quality of slab track has to be guaranteed by appropriated high-level quality assurance measures. This means extra costs and time for the construction works and their control.

Table 20. Construction cost of slab track systems [3]

SLAB TRACK SYSTEM	TOTAL (€/M)	RATIO SLAB VS BALLASTED
Ballasted track	350	1,0:1
Rheda	1198	3,4:1
Rheda-Berlin	630	1,8:1
Rheda 2000	1200	3,4:1
Rheda City	450	1,3:1
Züblin	550	1,6:1
SATO	600	1,7:1
FFYS	600	1,7:1
FTR	1750	5,0:1
ATD	600	1,7:1
GETRACK	625	1,8:1

SLAB TRACK SYSTEM	TOTAL (€/M)	RATIO SLAB VS BALLASTED
FFC	470	1,3:1
EDILON	470	1,3:1
Shinkansen	700	2,0:1
Balfour Beatty	1275	3,6:1
Floating slab (Railtech)	900	2,6:1

Figure 36 shows graphically the total construction costs referred in previous table. The Japanese Railway Agency, for example, required to the design of the Shinkansen slab track that construction costs shall be less than twice as much as that of ballasted track [39]. In the Rheda design type the construction costs amount to 1.5 times – and sometimes even much more – of comparable calculations for ballasted track, nevertheless this system is mainly used today because of the long-term experience.

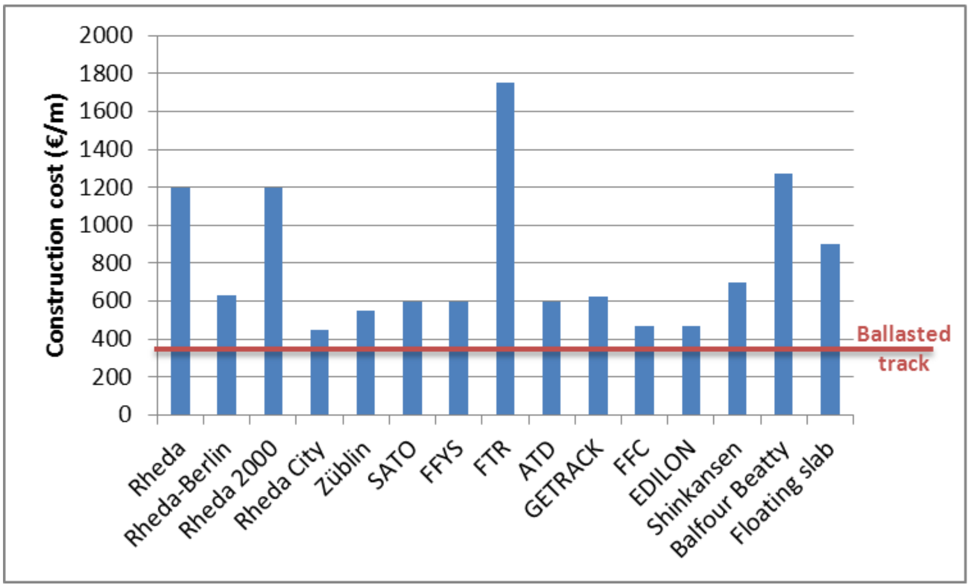


Figure 36. Construction cost of slab track systems

Recent feasibility studies states that, assuming adequate maintenance, slab track systems will be profitable only if its construction costs are no more than 30% above the ballasted track [3]. This means a construction cost about 450€/m, which could be considered as a requirement for the new slab track designs in order to be competitive enough.

10.2 Low maintenance costs

Economic efficiency of slab track as against ballasted track can be calculated only from the increased maintenance expenses required for ballasted track. The maintenance of ballasted track nowadays is, however, mechanised and automated to a great extent and cheap in comparison to the operation expenses. The development of permanent-way machinery shows that a higher and higher accuracy and performance for these machines achieves an increasingly durable track position.

The slab track to a certain extent also requires some maintenance, as mentioned in section 0. The long experience in Japan reveals that maintenance costs in slab track sections are from 18 to 33% less than ballasted track [2]. But repair costs for the slab track are complicated, cost-intensive and time-consuming. The operation hindrance cost in case of longer closures of slab track lines due to damage are extremely high and can hardly be calculated or predicted today. Mechanised and automated permanent-way machinery exists for ballasted track, but it does not for slab track.

The requirement for modular design (see section 7.3) will lead to faster and cheaper repair procedures, which will help to keep the maintenance costs of the new designs under control.

10.3 Long life cycle

Current life expectancy of slab track systems is about 60 years, while in ballasted tracks it is about 40 years (see Figure 37). The most usual problems that lead to the end of life of the system are the following:

- Fatigue strength of the rail fastening system and its components (intermediate layers, intermediate plates, angular guide plates, rail clamps, sleeper screws and anchor bolts)
- Fatigue strength of the reinforcement and concrete of the track base layers
- Fatigue strength of the elastic coating
- Fatigue strength of the grouting concrete and the substructure (according to application: concrete subbase, hydraulically bound base layer, anti-frost layer, tunnel floor etc.)
- Ageing of the components mentioned above

Manufacturers are currently working in solutions to increase the life cycle of their slab track systems by improving the reliability of the whole system and designing easy procedures to exchange individual components. The common target is to reach the 100 years of life expectancy, and this is the requirement for the new slab track designs.

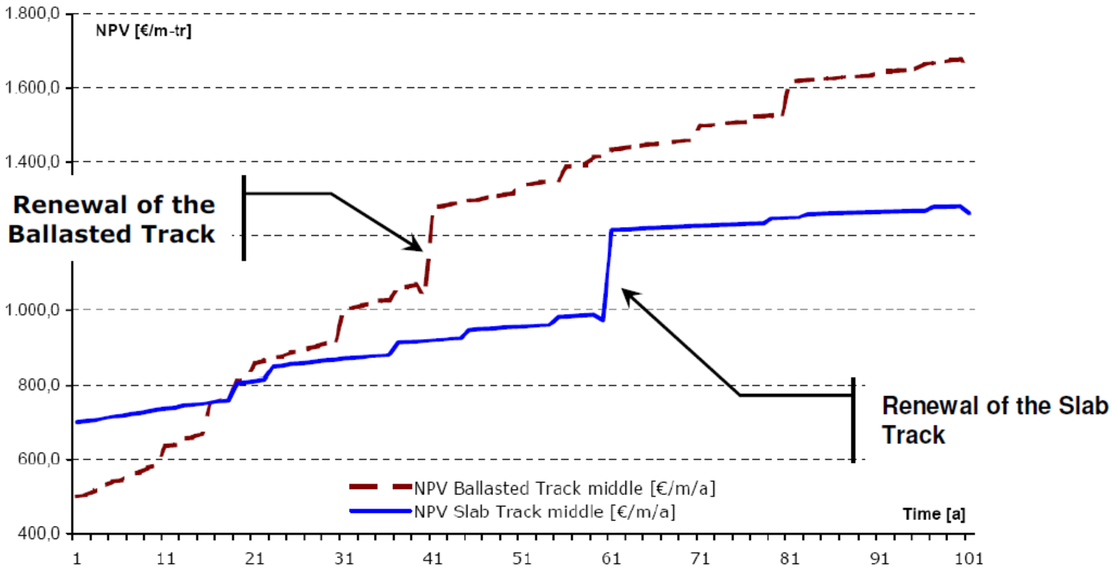


Figure 37. Comparative analysis of net present value in ballasted track and slab track [48]

11 REQUIREMENTS FROM THE TRACK LOADING DESIGN GUIDELINE

Track systems are required to resist vehicle loading while protecting their supporting layers. This is achieved by effectively spreading the loads from the wheel rail contact through to the sub-grade, in order to minimise permanent deformation over time and reduce risks of failure. This section provides an overview of all the track loads to be considered while designing and making calculation for a slab track, in relation to the dynamic interaction between vehicles and track.

11.1 A CLASSIFICATION OF LOADS

The vertical and lateral dynamic loads to be considered can be separated as per their frequency content, with associated influential parameters and type of damage they lead to:

- Quasi-static loads: they are the vertical ($\mathbf{Q_0}$, $\mathbf{Q_{qst}}$) and lateral ($\mathbf{Y_{qst}}$) contact forces at each wheel-rail interface which depends on the axle load and the added components due to vehicle non compensated acceleration in curves and vehicle curving abilities also refer to as 'nosing'.
    - $\mathbf{Q_{qst}}$ loads are influenced by vehicle uneven loading, traction elements in bogies as well as non-compensated accelerations in curves.
    - $\mathbf{Y_{qst}}$ loads depend on the combination of wheel and rail shapes, the bogie wheelbase, the suspension characteristics (spring and damping parameters), track geometry (curvature and cant) and vehicle speed (resulting cant deficiency).
- Low frequency dynamic loads (below 20Hz): $\mathbf{Q_{max\ <20Hz}}$, $\mathbf{Y_{max\ <20Hz}}$ and $\mathbf{\sum Y_{max}}$ (track shifting force) are forces typically associated with the vehicle dynamic behaviour (mass/inertias, spring and damping properties) and influenced by the track geometrical quality, quantified as per the standard deviation over 200m for horizontal rail level and lateral alignment in the wavelength range 1-25m [EN13848]. Longer wavelengths are also influencing the vehicle dynamic behaviour, especially at high speeds. Limit values are handled in the terms of vehicle certification in EN14363 and UIC518.
- Medium frequency dynamic loads (in the range 20 to 90Hz): $\mathbf{Q_{dyn\ <90Hz}}$ and $\mathbf{Y_{dyn\ <90Hz}}$ forces are generated from discrete events such as dip joints, weld repairs, surface defects and switches and crossings. They mostly generates an additional force component which amplitude and wavelength depends on the track stiffness and damping characteristics, the vehicle unsprung mass and its speed as well as the shape of the wheel or rail non-linearity. At this frequency the forces are traditionally referred to as P2 force in the vertical direction and regional specifications exist for defining limit values (e.g. Great Britain group standard GM/TT0088). They are transmitted to the supporting ballast and

subgrade layers and lead to settlement as well as fatigue issues with rails, bearers, and cast crossings.

- High frequency dynamics loads (above 90Hz): They are the higher frequency component of the above force, which includes the additional response from the wheel-rail mass on the contact spring, traditionally called the P1 force. Current standards are not considering this force due to its highly transient nature, although it may arguably contribute to the generation of local rail and wheel material surface and sub-surface defects.

11.2 Additional track load recommendation

In addition to the current TSI and EN standards load consideration (section 5.5.3) the following combinations of loads have been found to potentially be relevant for the design of new slab tracks to achieve a high performance design:

- Track twist $\mathbf{Q_T}$: This is uneven vertical loading across the slab track leading to torsional strain of the slab. This might be particularly relevant to the load transfer from one slab element to the next with discrete finite length slab construction.
- Gauge spreading $\mathbf{Y_{GS}}$: difference between the right wheel lateral force and the left wheel lateral force on each wheelset leading to gauge widening. These are generally high in tight curves.
- Bogie skewing $\mathbf{Y_{BS}}$: difference between the sum of the lateral force on the leading wheelset and the sum of the lateral force on the trailing wheelset, leading to lateral alignment defects.
- Bogie total $\mathbf{Y_{Bogie}}$: sum of the lateral forces on all wheels of a bogie leading to track shifting.
- Rail twist $\mathbf{Y_{RT}}$: sum the lateral force on each side of the track leading to rail twist and potential fatigue issues in rails.

11.3 Summary of recommended track loads

Table 21 summarises the current track loads specification found in relevant standards (EN 1991-2:2003, UIC518 and EN14363 and the working document EN16432), highlighting in grey those additional parameters which might be relevant for the further study and design of the C4R slab track.

11.4 Detailed analysis of track loading based on vehicle measurement data

Annex I contains the results of the quantification of track loads, both quasi-static and dynamics (<20Hz), based on vehicle measurement carried out in the prior EU project Dynotrain. The main conclusions of the study are summarised as follow:

- Heavy locomotive represent the most relevant load conditions to be considered

- Quasi-static loads are highly susceptible to track layout (radius) and running conditions (cant deficiency), showing that segmentation could be applied to the design process, .i.e. specific load limit for specific end applications.
- Accepted track shifting force limit are generally conservative
- Dynamic load factors could be expected to be reduced for the case of a slab track with respect to ballasted track as the geometrical quality should be improved.
- Other force combinations not currently addressed are significant and potentially relevant for the design of slab track.

Table 21. Track forces summary and relevant parameters

Quantity	relevant standard	Applied value	Influence factors	Notes
VERTICAL TRACK LOADS				
Q_0	EN 1991-2:2003	axle load or wheel load	vehicle type and payload	as per requirement (max axle load - mixed traffic - heavy freight)
NxQ_0	EN 1991-2:2003	minimum 2 axle bogie or 3 axle	vehicle type	see load model LM71 or specific vehicle
$Q_{0/m}$	EN 1991-2:2003	Q_0 / wheelbase	vehicle type	Axle load ratioed to 1m of track, see load model LM71 or specific vehicle
ΔQ_{qst}	EN 1991-2:2003 , UIC518	+/-25% of Q_0, $(Q_{qst})_{lim}$=145kN or 155kN (freight Q0>112.5kN and V<100km/h)	curvature, cross level, cant deficiency	effect of non-compensated accelerations in curves and also imbalance wheel load, vehicle/bogie types
$Q_{dyn\ <20Hz}$	EN 1991-2:2003, UIC518	$1.5x(Q_0+\Delta Q_{qst})$, $Q_{lim}=90+Q_0$ or fixed limit f(V)	suspension, speed, track vertical quality	Accounts for a dynamics factor
$Q_{dyn\ <90Hz}$	GMTT/8800	GB limit 322kN	unsprung mass, track stiffness/damping/mass, speed and dip angle	Equivalent P2 force
$Q_{dyn\ >90Hz}$	not considered	na	discrete defects, speed, wheel-rail contact	high frequency wheel-rail contact forces possibly contributing to wheel-rail surface and sub-surface damage
Q_T	not considered	na	suspension, curvature, cross level, cant deficiency	diagonal loading of bogie vertical forces, inducing torsional deflection at slab end
LATERAL TRACK LOADS				
Y_{qst}	UIC518, EN14363	$(Y_{qst})_{lim}$=(30+10500/Rm) kN	suspension, curvature, cross level, cant deficiency	for small and very small radius curves to check the outter rail lateral resistance (bending, welds, joint, fastenings…)
$Y_{dyn\ <20Hz}$	UIC518, EN14363	$10+Q_0/3$	wheel-rail contact, horizontal and alignment quality	dynamic lateral force in curves to check for outter rail resistance
$Y_{dyn\ <90Hz}$	GMTT/8800	71kN	stiffness/damping/mass, speed and lateral ramp discontinuity angle	Equivalent to P2 force in the lateral direction
$\Sigma Y_{2m,\ max}$	UIC518, EN14363	$\alpha(10+2/3Q_0)$, α=0.85 (freight), 1 (other)	suspension, curvature, cross level, cant deficiency	sum of the guiding force - sliding mean over 2m
$\Sigma y_{bogie,qst}$	not considered	na	suspension, curvature, cross level, cant deficiency	nosing force of 100kN (rail or axle - check)
$\Sigma y_{bogie,dyn}$	not considered	na	wheel-rail contact and track alignment quality	
Y_{BS}	not considered	na	suspension, curvature, cross level, cant deficiency	bogie skewing (diff. between leading/trailing axles)
Y_{RR}	not considered	na	suspension, curvature, cross level, cant deficiency	Rail roll or twisting - check values and incidence on fastening system
COMBINED VERTICAL/LATERAL TRACK LOADS				
B_{qst}	UIC518	$(B_{qst})_{lim}$=180kN or (30+10500/Rm) kN	suspension, curvature, cross level, cant deficiency	for small and very small radius curves to check the outter rail lateral resistance (bending, welds, joint, fastenings…)

12 REQUIREMENTS FROM THE CLIMATE RESILIENCE DESIGN GUIDELINE

Railway track materials and underlying soil layers are subjected to traffic loading and their mechanical behaviour is highly controlled by hydro-geological conditions, temperature, and water transfer resulting from atmospheric actions. Due to the porous nature of materials composing the different trackbed layers and its complex interaction with the surrounding environment, railway substructure plays a central role concerning the resilience of the overall track system when subjected to extreme climate events. Generally, railway trackbed layers are unsaturated and moisture changes and water flow are governed by suction variations. Water content variations, especially excess moisture in trackbed layers, combined with traffic loads, may significantly reduce the bearing capacity and stability (risk of collapse) of the railway substructure. In this context, it is fundamental to keep the railway trackbed layers and the subgrade dry enough to avoid any potentially harmful effects associated to the presence of water by reducing the amount that is free to infiltrate and percolate through railway substructure. Hence, an adequate design and maintenance of surface and subsurface integrated drainage system is needed in order to ensure suitable strength of the railway substructure providing an adequate resilience against environmental actions and extreme events.

There are several aspects that must be fully considered in order to design an appropriate drainage system for a railway track line section:

- Geometric characteristics of the railway track (layout and profiles);
- Drainage areas and existing drainage systems;
- Geology and soil nature;
- Atmospheric data (precipitation, relative humidity, temperature, wind velocity, frost);
- Hydrological and hydrogeological conditions (groundwater conditions, floods records).

An adequate assessment of the railway substructure resilience against environmental actions requires considering the complex Thermo-Hydro-Mechanical (THM) phenomena taking place between the trackbed materials and its surroundings. In fact, there exist a number of mutual interactions that must be taken simultaneously into account. In this context, finite element THM analysis of the railway track modelling spatial and temporal variations of physical, geomechanical and hydrogeological material properties provide an effective tool regarding an adequate design of the different components. Also, the use of this numerical approach is suitable to evaluate the resilience of different design solutions when facing extreme environmental scenarios [49].

In order to evaluate the resilience of different design solutions when facing extreme environmental scenarios, a finite element model of the railway substructure was developed and a several THM analyses were performed. Different design features were reviewed such as track configurations, geometric layout, local soil general properties, traffic conditions, surface and subsurface drainage systems, phreatic level location, reference climate and hydrogeological characteristics. Also, different extreme events scenarios are presented including floods, major temperature variations, rapid groundwater table raising and failure of drainage components. Figure 38 presents an example of the developed finite element THM model illustrating part of the total discretised domain (mesh), general boundary conditions, and the physical processes involving water and temperature transfers. The developed model allows the incorporation of surface and subsurface drainage components. A detailed description of the finite element THM model developed by IST as well as the different considered case studies are presented in Annex II (Track Resilience to Natural Events: Design Guidelines).

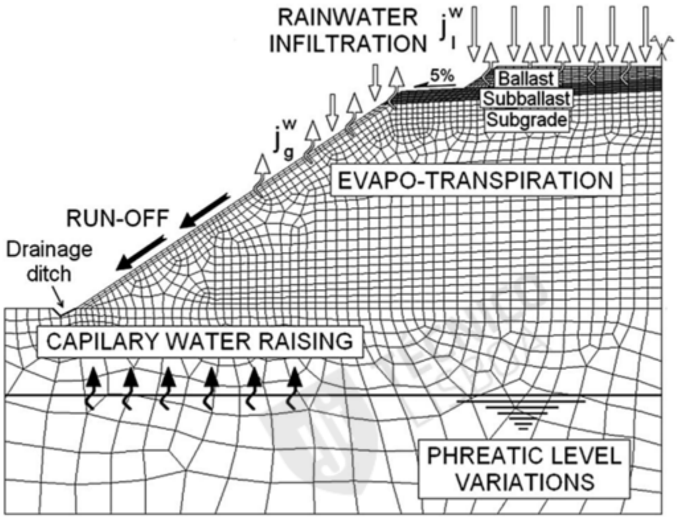


Figure 38. Two-dimensional Finite Element model: THM Phenomena, Mesh and Boundary Conditions. [50]

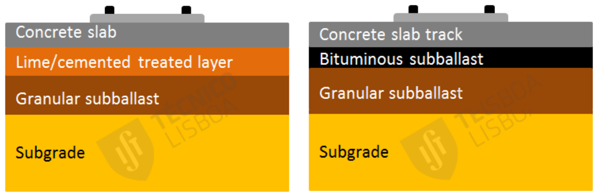
Track design variables are determined during the design stage, executed in the construction of the phase and will influence the overall behaviour of the railway track along the entire service life. Hence, these design variables must be appropriately analysed and adequately chosen in order to allow for a suitable performance of the different components. Table 22 presents a summary of the influence of the main track design variables to be considered when assessing the resilience of the railway substructure against environmental actions.

Table 22. Track design variables to be considered controlling the resilience against environmental actions. [50]

TRACK DESIGN VARIABLES

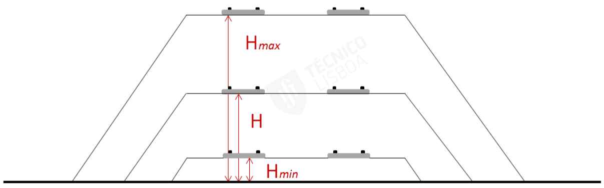
Track Configuration

The adopted tracked design solution highly impacts on the overall thermo-hydro-mechanical behaviour of the railway structure. Various materials may be combined to better fulfil the functions of the different trackbed layers.



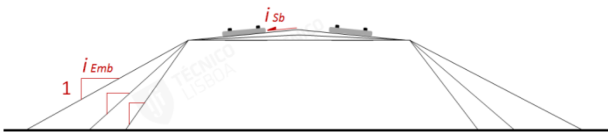
Height of Embankment

Consolidation processes of soil and granular materials gain relevance as the height of the embankment increases. Instability mechanisms associated to water infiltration and stresses changes need to be adequately considered.



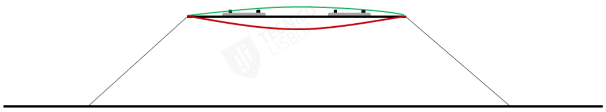
Cross Slope of the Subballast and Embankment

The transversal geometry influences the amount of run-off and infiltrated water during a rainfall event. It also defines the preferential percolation paths and water pressure distributions.



Characteristics of Trackbed Materials

The gradation of the granular materials and their physic-chemical properties highly affects the hydro-mechanical behaviour of the railway track and the fulfilment of its main functions. The use of collapsible and expansive soils must be carefully assessed due to potential inadequate deformational behaviour and instability problems.



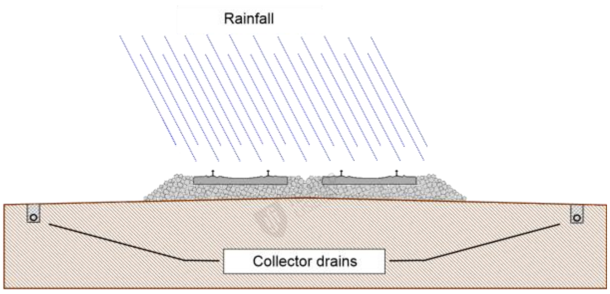
Drainage Components

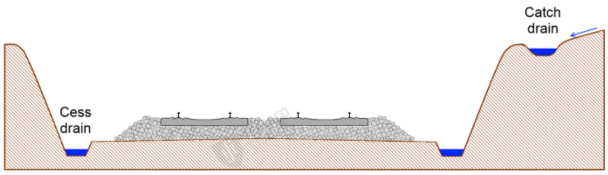
Water significantly affects the structural behaviour of the railway track. During extreme events, water infiltration and percolation may compromise the overall integrity of the substructure. The main sources of water affecting the railway track are:

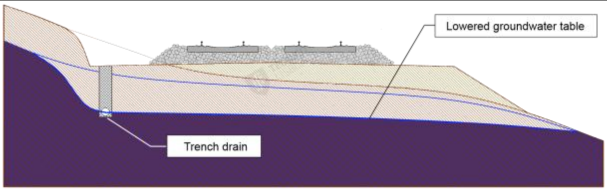
Rainfall directly on the track structure
Surface water flowing toward and infiltrating the track structure
Groundwater table

An adequate surface and subsurface drainage system must be design with the aim of collecting and diverting surface water away from the track reducing the available water to infiltrate and deteriorate the track substructure.

Surface longitudinal drainage components such as cess and catch drains may be designed to intercept overland flow or runoff before it reaches the track. Subsurface drainage components must be designed to appropriately drain track substructure and control the groundwater

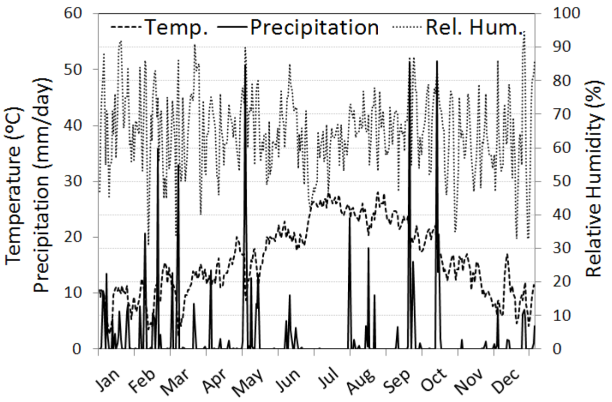
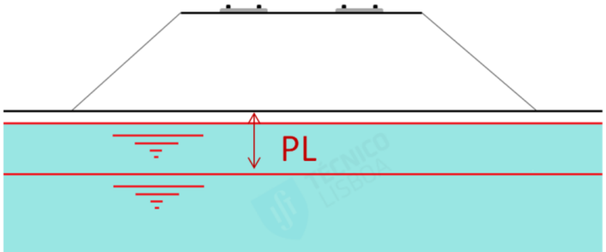




level, thus reducing the amount of water percolating inside the trackbed layers.	

Along with traffic loading, environmental events are the main factors responsible for the process of track deterioration. Atmospheric conditions affect the THM behaviour of the railway track with particular influence within the first 2 to 5 meters below the surface. Nevertheless, the behaviour of inner parts of the substructure and its hydro-static profile are strongly controlled by hydrological variables such as the position of the groundwater table which result from broader regional hydro-geological equilibrium conditions. presents a brief description of the environmental actions affecting the thermo-hydro-mechanical behaviour of the railway substructure and that must be considered for modelling purposes.

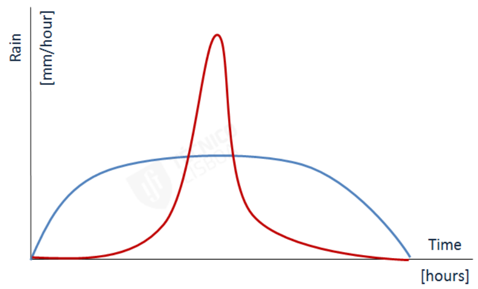
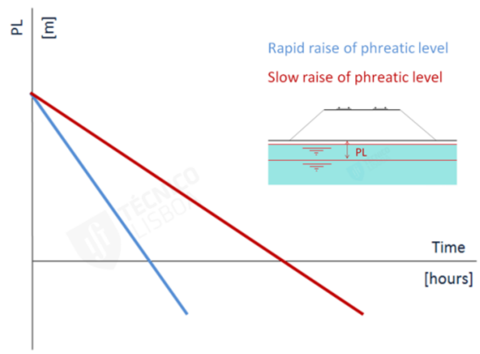
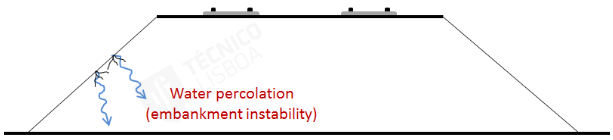
Table 23. Environmental actions affecting the THM behaviour of the railway substructure [50]

ENVIRONMENTAL ACTIONS	
Reference Climate and Atmospheric Conditions Being subjected to environmental actions, complex thermal, hydraulic and mechanical phenomena occur between the atmosphere and railway trackbed layers. In the initial years after construction, railway substructure experiences a process of thermo-hydro-mechanical adaptation towards environmental equilibrium conditions controlled by atmospheric and hydro-geological variables. A reference climate is characterised by atmospheric conditions (e.g. rain, temperature, relative humidity, wind, solar radiation) varying between typical ranges and associated to more or less well stable patterns. However, an increase in the frequency of extreme environmental events is being forecasted for the future decades which reinforce the importance an adequate thermo-hydro-mechanical modelling of the railway substructure.	
Groundwater Table Location Depending on regional hydro-geological conditions and also related to the geometric layout of the railway track (cutting or embankment), the position of the groundwater table defines water and moisture distribution inside the track substructure. Deep groundwater tables are associated to dry subgrades while high phreatic levels lead trackbed materials to be close to saturated conditions.	

Finally, Table 24 describes several extreme environmental scenarios suitable to evaluate the resilience of the substructure against extreme events. Higher temperature ranges, more frequent and intense environmental events will probably find weaknesses in drainage components and vulnerabilities in track substructure that need to be properly addressed and prevented. Subgrade can become unstable either in a progressive manner or suddenly. Sudden substructure failure rarely occurs, unless there is an extreme environmental event such as high rainfall and flooding or a large increase of load conditions acting on a subgrade composed by soft or marginal soils. Drainage problems or water infiltration due to poor drainage design (lack of capacity) may worsen this problem by reducing soil strength and leading to excessive deformation or unstable (collapsible) ground conditions.

In the case of extreme rainfall scenarios, it is of particular relevance the analysis of the antecedent conditions preceding the extreme rainfall event. The hydro-mechanical response of the railway substructure during an extreme rainfall is highly controlled by the precedent unsaturated state of the soils. An extreme rainfall event tends to generate more structural instability whenever it is preceded by an antecedent rainfall or snow melting process. In cases when previous saturation of the soils does not exist, the infiltration of the rainwater produced during an extreme rainfall event is lower, the run-off of superficial rainwater is higher and the total amount of rainwater percolating inside the substructure and contributing to potential instability processes is reduced.

Table 24. Environmental scenarios to evaluate the resilience of the railway substructure against extreme events. [50]

EXTREME ENVIRONMENTAL SCENARIOS	
Floods Depending on the permeability of surface materials and on the characteristics of a particular rainfall event, these episodes may originate floods having a high destructive potential. Important rainfall events increase the amount of water infiltrating the track substructure as well as the collected runoff water in drainage components. Hence, the response of the railway track must be adequately assessed in terms of the intensity-duration-frequency relationships of extreme rainfall events characteristics of a given area. The antecedent rainfall to a major event also plays a fundamental role in the response of the railway substructure and must be adequately considered. Depending on the local (or regional) hydro-geological conditions, an extreme environmental episode may also affect the overall subsurface hydraulic equilibrium leading to significant variations of the groundwater table which must be suitably considered in terms of the rate at which the	
Extreme Temperature Variations High temperature variations may be responsible for the appearance of cracks in railway track components offering preferential paths for rainwater and run-off water to infiltrate and percolate eventually reaching	

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the core of the embankment. In this situation, the combination of water and high stress levels might be potentially destructive for substructure stability.
Cyclic alternation between wet and dry conditions, particularly episodes where high suction profiles establish within the embankment, may be responsible for the development of cracks in the side slopes of the embankments. Furthermore, temperature variations may generate thermal cracking of the concrete slab which must be adequately considered in the design.
Low temperatures leads water present in the trackbed layers to freeze. Then, snow melting generates water flows which increase the susceptibility of the substructure to fail under an extreme weather event.
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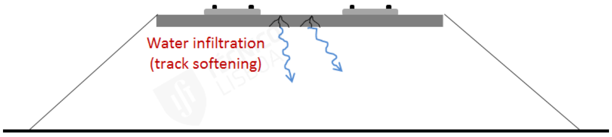

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Drainage Mal-functioning
Extreme environmental events have the potential to cause instability problems on the substructure by themselves. However, when combined with mal-functioning of drainage components the effects might be destructive. In case of cess drains failure, runoff water from the track and water flowing from adjacent slopes will be collected but not removed throughout the rest of the drainage system. Also, in situations when a trench drain is obstructed, its main function of lowering the groundwater table is not fulfilled. Drainage mal-functions result in an excess of pore water pressures in the substructure reducing soil strength and resistance. Hence, an adequate design of the different drainage components and its capacity is mandatory. High resiliency of the substructure against extreme events might require an adequate level of redundancy within the drainage system.
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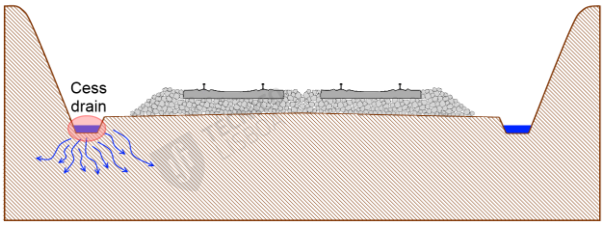

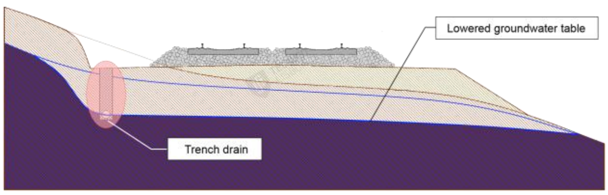

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13 REQUIREMENTS FROM THE COST & RAMS ORIENTED DESIGN GUIDELINE

The principal objective of this third guideline is to develop and to analyse a combined design of cost and RAMS methodologies for an existing track technology, in order to make easier a future study for new designs.

The analysis of the RAMS parameters (Reliability, Availability, Maintainability, Security) is one of the most complete and important method to compare the performance of the systems and to determine the Reliability, Availability, Maintainability and Safety requirements.

The RAMS of a system can be characterized as a qualitative and quantitative indicator of the degree that the system, or the sub-systems and components comprising that system, can be relied upon to function as specified and to be both available and safe.

The attached paper aims to analyse the costs and RAMS parameters of a High Speed ballasted track in operation in order to estimate the Reliability, Availability, Maintainability values that let analyse possible improvements for the new designs, as for example modular plug and play design.

In a complex system as a high speed line is, the fulfilment of a total RAMS study is complicated due to the great amount of systems and subsystems and the relations between them. Because of this, the present paper focus its scope in making a RAMS study based on real data of the infrastructure and superstructure subsystems of a high speed line. It is worth to mention that the subsystems will be analysed in **ballasted track**, because of the lack of availability of failure data in slab track.

RAMS analyses usually cover the entire Life Cycle of a system; nevertheless this study is focused in one of the last phases of the life cycle, **operation and maintenance**.

The chosen case study is one of the Spanish high-speed railway lines with the higher number of kilometers with slab track. Nevertheless, there are not failures detected up to date on the slab track system, so the study will focus on the stretch built on ballasted track.

This line has around 200 kilometres of double track, of which 37 km are built on slab track inside double tube tunnels, being the operational speed 300 km/h.

The systems studied are the railway superstructure and infrastructure, getting the study ready to its later integration with other railway systems. Furthermore it is studied the Life Cycle Cost (LCC) of the superstructure and infrastructure systems during the phases of construction and maintenance. It is made a costs study of ballasted track and slab track systems during the phases of “construction” and “operation and maintenance”, based on the experience obtained of several Spanish high speed lines and stretches.

The RAMS study will be performed by a statistic analysis, trying to differentiate events or failures by track, by affected elements, by years, etc. To this end, the superstructure has been divided into the following subsystems:

- Ballast
- Rail
- Fastenings
- Sleepers
- Track geometry (Levelling and alignment failures detected by dynamic auscultation)

For each one of the previous superstructure subsystems, the RAMS parameters have been calculated from obtained real data.

It is very important to emphasize that the AVAILABILITY obtained according to the methodology developed in this paper can differ from other availabilities calculated according to different criteria (as for example, from the availability calculated in base to the delays of the trains running). The availability obtained in this document only depends on the failure parameters of the system, so it is of the system its own, independently of the use that is made of it (and not of margins that could have the movement of trains to consider them delays). In other words, this is an AVAILABILITY OF THE SYSTEM ITS OWN, AND IT IS NOT AFFECTED BY THE COMMERCIAL EXPLOITATION OF IT.

Listed below are general conclusions about the **superstructure subsystems** in the analysed case study:

About the Track Geometry subsystem (Dynamic auscultation)

- There are no points where the “immediate action defects” have been repeated frequently, because when they are detected, they are repaired in a very brief time. From 2011 onwards, these defects, detected by the dynamic auscultation train, almost do not exist. It is therefore a great MTBF (Mean Time Between Failures) value.
- The Mean Time to Repair (MTTR) in the case of the “immediate action defects” is approximately 3 hours, time that is covered by the maintenance time window
- The time that pass since the failure is detected by the dynamic auscultation train until the “immediate action defect” is repaired (including the analysis time of the data recorded by the dynamic auscultation train) is lower than 5 days
- The average AVAILABILITY of the studied line related with the Track Geometry subsystem (dynamic auscultation) is 100%, because no defects have caused any Temporary Speed Limitation, and the availability of the superstructure have not been affected
- It is worth stressing that the Preventive Maintenance actions scheduled on this railway line prevent from the appearance of a large number of “immediate action defects”

About the SLEEPERS subsystem:

- Once analysed the data, with the obtained results it can be said that the more significant failures correspond to “hit sleepers” particularly on the year 2012. Most of these defects are caused by the maintenance works that are carried out by heavy machinery (preventive and corrective maintenance works) and can damage the sleepers while other superstructure defects are being corrected.

About the RAIL subsystem:

- Once analysed the data, with the obtained results it can be said that the more significant failures detected on the rail are located in weldings, while other defects are practically imperceptible.

About the BALLAST subsystem:

- It is detected that the more predominant failures are the scarcity of ballast and the absence of track bed profiling. These defects mostly occur at the beginning of the operation. After these defects are repaired, the ballast track bed keeps in good condition.

About the FASTENING subsystem:

- With the obtained results it can be said that the more predominant failures are the absence of clips and the scarcity of tightening torque.

Both in case of sleepers, rail, ballast and fastenings the repair of the defects or the replacement of damaged elements takes place into the maintenance time window. As the defects, up to date, have not caused any Temporary Speed Limitation, the AVAILABILITY of the Superstructure system is 100%.

14 CONCLUSIONS

A set of functional and technical requirements have been defined for the design of new track concepts within the scope of C4R-SP1. These requirements are based on the regulatory framework (TSIs and national standards) and the features of existing track systems, as starting point, and shall be updated with the requirements derived from other SPs, in particular SP2 and SP5.

When possible, the requirements have been differentiated between high-speed and mixed traffic, according to the scenarios set out in the DoW, which correspond to the following line categories:

- Category I: High-speed lines. New lines for speeds of at least 250 km/h.
- Category IV: Conventional rail lines. New core TEN lines. Mixed traffic.

It is worth to mention that, as a first approach, the new track systems will be designed only for plain tracks, therefore no requirements have been described for particular designs at transition zones or S&C.

Following, the complete list of requirements is shown.

- Geometrical requirements:
  - Cost-effective track and layout parameters
  - Reduced height and weight
  - Enough space for signalling and electro-technical equipment
  - Earthing of the metallic parts
  - Electrical isolation of the rails
  - Facilitation of drainage
- Mechanical requirements
  - Non-setting subsoil
  - High quality of supporting structure
  - High quality of earth work
  - Adequate track stiffness
  - High track resistance
  - Compatibility with bridge movements
- Environmental requirements
  - Possibility to install noise and vibrations absorbers
  - Use of waste materials
  - Non-contaminant leachate
- Construction requirements
  - Low number of construction steps
  - Fast construction
  - Modularity
  - Easy transport of precast elements to construction site
  - Easy alignment of track panels

- Maintenance requirements
    - Low maintenance
    - Easy replacement of track components
    - Friendly repair procedures on unforeseeable events
- Operational/safety requirements
    - Performance parameters
    - Compatibility with linear eddy current brakes
    - Track accessibility to road vehicles
    - Integration of/compatibility with derailment protection devices
    - Electromagnetic compatibility
- Cost requirements
    - Low construction cost
    - Low maintenance costs
    - Long life cycle

The design requirements are accompanied by three specific guidelines, which address some of the most innovative concepts in track design:

- Annex I: Track Loading Design Guideline
- Annex II: Climate Resilience Design Guideline
- Annex III: Cost & RAMS oriented Design Guideline

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