Slab Track Systems for High-Speed Railways

Master Degree Project

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Preface

The last fifteen years many railway projects took place in Greece especially in Athens. The most important was the construction of Athens metro which is still expanding. One of my best friends Dimitrios was doing his placement with Attiko Metro and he invited me in the construction site. This was the first time I saw a ballastless track. After many years, I decided to come to Stockholm for my masters. The time I wanted to find a subject for my thesis I heard about a railway expert we had in our school. I immediately decided to meet him and discuss about a possible masters project within railways. This expert was Dr. Elias Kassa. Very soon he accepted to be my supervisor and inspired me to work hard. I would like to thank him very much for the valuable comments and directions he gave me in order to produce the best possible outcome. There are many people who helped me during this study and I would like to express my gratitude to them. Special thanks to my good friend and colleague Huan Feng who helped me a lot in the modeling part and his comments on my work. I am grateful to my friends Panos Gkouriotis and Antonis Karalis for their emotional support and good company during this period. Finally, I would like to thank my family for the financial support during this period as well as for their love and patient.

Stockholm, May 2012

Georgios Michas
Abstract

In the last 40 years an increase in train speed and axle load around the world and other challenges in the conventional ballasted track system gave birth to ballastless railway track system. This study examines in depth the various slab track systems that are being used today. Their design characteristics as well as the various requirements for efficient use are thoroughly explained. At least 34 different ballastless systems have been recorded in many railway networks throughout the world. The most significant slab track systems are analysed in detail and compared. Slab track designs have significant advantages comparing to ballasted tracks. The most significant are the high stability of the track, the almost non-existent need for maintenance, the long life cycle (60 years) and the reduced weight and height of the track. Their disadvantages against the ballasted tracks are mainly summarized in their higher construction costs. The Finite Element package ABAQUS/CAE is used to model a 3-D slab track design under static traffic loading. The results suggest that slab tracks have profoundly better stability and durability comparing to ballasted tracks mainly due to their higher stiffness and strength. The author underlines the need for further studies to undoubtedly prove the claimed advantages of slab track systems as well as to improve the costs associated with construction.

Keywords: Railway slab track, High-speed tracks, Finite element analysis, Rheda, Maintenance, Life Cycle Cost
### Abbreviations

<table>
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<th>Description</th>
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<tr>
<td>ABL</td>
<td>Asphalt Bearing Layer</td>
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<tr>
<td>ATD</td>
<td>AsphalTragschicht mit Direktauflagerung - Asphalt rail span with direct Support</td>
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<td>BBERS</td>
<td>Balfour Beatty Embedded Rail System</td>
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<td>BES</td>
<td>Betontragschicht mit EinzelStützpunkten - Concrete bearing layer with individual support points</td>
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<td>BTD</td>
<td>BetonTragschicht mit Direktauflagerung - Concrete supportive layer with direct support</td>
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<td>BTE</td>
<td>BetonTragschicht mit Einzelstützpunkten - Concrete bearing layer with individual support points</td>
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<td>CBL</td>
<td>Concrete Bearing Layer</td>
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<td>ERS</td>
<td>Embedded Rail Structure</td>
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<tr>
<td>FFC</td>
<td>Feste Fahrbahn Crailshein - Slab track Crailshein</td>
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<td>FPL</td>
<td>Frost Protection Layer</td>
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<td>FST</td>
<td>Floating Slab Track</td>
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<td>HBL</td>
<td>Hydraulically Bonded Layer</td>
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<td>HMA</td>
<td>Hot Mix Asphalt</td>
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<td>LCC</td>
<td>Life Cycle Cost</td>
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<td>LVT</td>
<td>Low Vibration Track</td>
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<td>LWR</td>
<td>Long Welded Rail</td>
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<td>PACT</td>
<td>Paved Concrete Track</td>
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<tr>
<td>SATO</td>
<td>Studiengesellschaft Asphalt Oberbrau - study group for asphalt superstructure</td>
</tr>
<tr>
<td>SBV</td>
<td>Schwellen mit BitumenVerguss (German) - Sleepers with bituminous poured mass</td>
</tr>
<tr>
<td>SFF</td>
<td>Schwingungsgedämpfte Feste Fahrbahn - Vibration damped slab track</td>
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<td>UIC</td>
<td>International Union of Railways</td>
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1 Introduction

1.1 Aim of the study

The purpose of this study is to thoroughly analyze the slab track concept and to underline its positive and negative sides. A comparison between ballasted and ballastless tracks is essential in order to clearly identify when and where the slab track systems perform better. A simple numerical model is developed to make a comparison between ballasted and ballastless tracks. However, it is not the intention of this study to suggest which track system suits one specific condition, and the results from this comparison are preliminary and it is not recommended to use the results from this comparison to arrive a final conclusion.

1.2 Background

The first slab track systems appear long ago, approximately at the beginning of the twentieth century, but their extensive development and use started at 1970’s. After 40 years of experience with slab track systems the information about their overall performance is enough to at least start seriously investigate and discuss if they fulfill or not the expected performance. The increased railway speeds nowadays are making the slab track concept more attractive than ever before. Most developed and many developing countries in the world have high speed lines (~300km/h) and they are preparing to update their existing lines as well as to create new high speed railway routes. A representative example is the High speed 2 project in UK. A high-speed (250mph) Y-shaped rail network will connect London, Birmingham, Leeds, Manchester, Sheffield and the East Midlands (Justine19). In many cases slab track systems seem to have the capabilities to serve these high speed routes more efficiently than the ballasted tracks mainly due to their higher structural stability, significantly lower need of maintenance, and longer life cycle (Esveld5). Big discussions in railway industry have emerged questioning the validity and credibility of the expected long term performance of the slab track systems. Many researchers have set the goal to unfold the truth about their limits in order to help the railway experts make the right choices. It is hoped that this thesis contributes to this direction and fills in ‘a small piece of the puzzle’.

The second chapter is devoted to the description of the general slab track structure analyzing each track bed layer in details. The standard requirements for noise/vibration effects, transition areas, signaling and electrical equipment as well as construction of slab track in tunnels and
bridges are thoroughly presented and discussed. Transition points as well as noise and vibration emissions are rigorously examined and discussed presenting several studies conducted in these fields the last years.

Chapter 3 deals with the numerous slab track systems that have been built and used the last four decades. The ballastless systems are divided in two main categories: the discrete rail support and the continuous rail support. These two categories are divided in subcategories which contain 34 slab track designs that have been used worldwide. Most of the slab track designs are analyzed in details providing information concerning their geometry, structural behavior and in many cases their construction methods.

In the fourth chapter a comparison between the various slab track systems is taking place in terms of flexural stiffness, geometry, track alignment, technically and economically as well as in total construction in km around the world. All systems have their own unique characteristics indicating their capabilities. The selection of the right slab track system in a project is based on this knowledge.

The advantages and disadvantages of slab track and ballasted track are analyzed in the fifth chapter. It is essential to recognize their strong and weak points in order to efficiently compare them. A comprehensive economical comparison as well as an overall performance comparison in terms of stability and maintenance need is performed based on several studies conducted in the past.

A 3D slab track model is built in ABAQUS to observe its behavior under static loading. A general linear static analysis is performed and the results are compared with those obtained in a similar ABAQUS simulation for a ballasted track. The results are presented and discussed in terms of deflection and stress diagrams. To build this model the author used the structural properties and geometry of the Rheda 2000 German slab track.

The final chapter summarizes the findings of this study discussing the overall performance of the slab track systems against the ballasted tracks. To improve the existing knowledge in slab tracks and be able to illustrate their advantages with certainty, the author makes some recommendations for future studies.
2 What is Slab Track

The so-called slab track is a concrete or asphalt surface that is replacing the standard ballasted track. This structure is made of stiff and brittle materials, hence the required elasticity can be obtained by inserting elastic components below the rail or/and the sleeper (Lichtberger\textsuperscript{22}).

Concrete is the prevailing material in slab track applications throughout the world. Only in very special occasions asphalt has been used as material for slab track constructions, and this is due to its high construction demands (Talampekos\textsuperscript{41}).

The slab track design can be found mainly in civil structures in high-speed lines and light rail. There are two different approaches of slab track design, and these are discrete rail support and continuous rail support (Esveld\textsuperscript{5}). There are many different slab track designs based on these approaches and they are analyzed in detail at chapter three.

What defines which track design is the most suitable depends mainly at the soil conditions. Each slab track system has different flexural stiffness, which should reckon in according to soil conditions because the whole system depends solely in its bearing capacity. When the soil for instance is soft a system with high flexural stiffness is needed in order to act as bridge across weaker spots and local deformations in the substructure (Esveld\textsuperscript{5}).

The whole structure is mainly composed from five layers as shown in figure 1, subgrade or subsoil (foundation), frost protective layer, hydraulically bonded bearing layer, Concrete/Asphalt bearing layer, and the rail (Franz\textsuperscript{29}).

![Figure 1: Three usual construction profiles for slab tracks (Darr\textsuperscript{11})](image-url)
In the following subchapters the requirements of slab track are described and analyzed in detail.

2.1 Slab track requirements

There are several specific requirements that need to be addressed before the design and construction of a slab track. According to the bibliography (Lichtberger\textsuperscript{22}, Profillidis\textsuperscript{28}, Esveld\textsuperscript{5}, Talampekos\textsuperscript{40,41}) these requirements are shaped mainly in accordance with the ground conditions, the chosen slab track design, the supporting layers underneath the slab, the location to be build such as in a tunnel or a bridge where most transition points are met, the materials, the traffic, the load per axle, noise restrictions, level of maintenance, construction costs, weather conditions, signaling and electronic systems to be used as well as passenger comfort.

2.1.2 Subsoil conditions

The slab track requires stable subsoil basically free of settlements in order to perform adequately. This is why most times slab track is found in tunnels and bridges (Lichtberger\textsuperscript{22}). It is a fact that the adjustments to the track geometry after construction are very limited, hence special preparation of the subsoil before construction is essential (Esveld\textsuperscript{5}).

The substructure requirements are the following:

1. The substructure of slab track must be secured down to a depth of 2.5m below the bearing plate by special earthwork treatments (Lichtberger\textsuperscript{22}).
2. A frost protective layer not less than 70cm thick should be applied to keep frost away from the bearing layers (Lichtberger\textsuperscript{22}).
3. In case of embankments the lower bearing layer should not be less than 1.80m thick and it should be made up of the top layer of the filling, for cuttings – of the soil below, or the soil has to be exchanged, if the bearing capacity of the existing soil is insufficient (Lichtberger\textsuperscript{22}).
4. In case of soft cohesive or organic soils the safer solution is to exchange them at a depth not less than 4m from the upper edge of the track (Lichtberger\textsuperscript{22}).
5. The ballast in slab track construction is replaced by a concrete or asphalt bearing layer (Lichtberger\textsuperscript{22}).
6. The adjustment capabilities of the slab track in elevation vary between +26 and -4 mm. In case of adjustments due to construction errors the allowed elevation changes are +6 and -4 mm. The rest 20 mm must be kept for necessary adjustments due to the possibility of future settlements (Talampekos⁴⁰).

7. The lateral displacements may be compensated within a range of ±5 mm. In case of construction errors only ±1 mm adjustments are allowed (Talampekos⁴⁰).

8. To use the slab track the groundwater should be at least 1.5 m below the head of the rail (Talampekos⁴⁰).

9. To carry out the essential geotechnical assessments, ground-probing at least every 50 m is required (Darr & Fiebig¹²).

10. The modulus of elasticity of the top surface of the substructure taken from the second load step in a plate loading test for newly constructed track should be \( E_{v2} \geq 60 \text{ N/m}^2 \) and for existing tracks this should be \( E_{v2} \geq 45 \text{ N/m}^2 \) (Esveld⁵).

### 2.1.3 Concrete bearing layer

According to Lichtberger²² the concrete bearing layer should satisfy the following features:

- The required profile tolerance on the surface of concrete bearing layer is ± 2 mm.
- The quality of concrete should correspond to quality B35 and should be highly resistant to frost.
- The cement content of the concrete should be between 350 and 370 kg/m³.
- The necessary reinforcement to limit the formation of cracks must be between 0.8 and 0.9% of the cross section of the concrete. This standard ensures that the width of cracks will not exceed 0.5 mm.
- The typical overall height is 200 mm.
- In the case of a design without sleepers the surface is cut at intervals of about 2 m to reassure controlled crack formation.
- The concrete layer can be mounted after it has achieved a minimum resistance to pressure of more than 12 N/mm².
- Any increase in the thickness of the concrete layer results in higher bending loads, hence a minimum allowable thickness of 180 mm should be observed.

Few extra details about the concrete bearing layer are mentioned in Talampekos⁴⁰. A finisher is used to lay the concrete bearing layer and the width of only one line is \( \geq 3.16 \text{ m} \). In case the concrete bearing layer is reinforced to reduce cracking, the reinforcement is placed at the center of the slabs cross section and it is usually consisted by longitudinal \( \phi 20/20 \) and lateral \( \phi 16/40 \) reinforcement. The concrete should have adequate chemical resistance.
2.1.4 Asphalt bearing layer

Some key facts about the features of the asphalt bearing layer are (Lichtberger22):

- The asphalt bearing layer is applied in four different layers with a total standard thickness of 300 mm.
- The required construction tolerance on the surface is ± 2 mm.
- Running on the asphalt bearing layer is allowed when the temperature is below 50°C.
- The asphalt surface has high sensitivity to UV-rays, hence the surface must be protected by spreading stone chips, gravel etc.

2.1.5 Hydraulically bonded bearing layer

A hydraulically bonded bearing layer is a mix of aggregates with a bonding agent placed under the concrete or asphalt bearing layer and contributes to an increase in the total bearing capacity of the entire system (Lichtberger22). This layer is lying on the frost protecting layer and its average compressive strength after twenty-eight days is 15 N/mm² (Talampekos41). Some key features of this layer are the following:

- The typical thickness of the layer should be 300mm (Lichtberger22)
- The laying of the hydraulically bonded bearing layer is carried out by a road finisher usually in two layers of thickness ≥ 12 cm and their connection should be obtained while they are still wet (Talampekos40).
- As the finisher lays the hydraulically bonded layer, automatically creates pseudo joints every 5 m with thickness 35% of the total thickness of the layer in order to control and reduce cracking (Talampekos40).
- A mix of mineral aggregates is used like sandstone, crushed sand and stone chips. The maximum grain size should not exceed the 32 mm (Lichtberger22).
- Portland cement is used as bonding agent, and its content is around 110 Kg/m³ (Lichtberger22).
- The minimum width of the layer is 3.8 m and the deviations of thickness from the anticipated level should be ≤ +0.5 cm and ≤ −1.5 cm (Where + is upwards and – downwards) (Talampekos40).
- The edges of the hydraulically bonded layer should be constructed with an outward ≥4% inclination to prevent water infiltration between the hydraulically bonded bearing layer and the concrete or asphalt bearing layer (Talampekos40).
- The hydraulically bonded layer should contribute to achieve a modulus of deformation of $E_{v2} \geq 120 N/mm^2$ on the top surface of the frost protection layer (Lichtberger22).
2.1.6 Frost protective layer

According to Lichtberger\textsuperscript{22} this layer is protecting the upper layers from frost; it can also compensate the differences in stiffness of the various layers towards the subsoil and leads the surface water away rapidly. It is resistant to weathering and frost and is consisted of fine gravel to prevent water from rising from the subsoil. This layer should have very low permeability values ($1 \times 10^{-5}$ or $1 \times 10^{-4} \, m/s$) to serve adequately. According to Talampekos\textsuperscript{41} the modulus of deformation at least at the upper part of this layer should be of $E_{v2} \geq 120 \, N/mm^2$. To achieve that, the upper part of this layer should be laid with materials similar to the above hydraulically bonded bearing layer.

2.1.7 Noise emissions and vibrations

As stated in Lichtberger\textsuperscript{22}, the slab track produces significantly higher noise radiation compared to the ballasted track. The noise has been recorded to be $+5$ dB more than that in conventional ballasted track. The reason is the uncoupling of the rail fastening and the lack of noise absorption of the ballast bed. Hence the higher noise emissions are solely produced due to the nature of the slab track structure and are profoundly increased within the frequency range of 250 to 1000 Hz. Many solutions have been investigated and finally recommended as appropriate to resolve the noise and vibration problems but all of them lack either in serviceability lifetime either appear to be very expensive or both. Noise absorbing material, noise protective barriers, acoustically innovative slab tracks (soled sleepers) are some of the proposals, which deal satisfactorily with the noise reduction.
2.1.8 Further studies in noise emissions and vibrations

In a study carried out in Singapore by Cui and Chew\textsuperscript{13} the effectiveness of a floating slab track to stationary and moving harmonic loads was investigated by using the so called receptance method. In more details, the Singapore Mass Rapid Transit System (SMRT) use in tunnels through sensitive areas, where ground borne vibrations cause problems to the industrial or/and commercial activities, concrete sleepers set in a continuous concrete slab referred to as fixed slab type (FT), and floating slab track (FST) which consists of discrete concrete units supported by resilient pads. The natural frequency of the floating slab system is designed to be 10 Hz. It is known though that after aging this frequency may increase to 12\textasciitilde24 Hz. The analyses of these two systems illustrate that the FST can perform adequately and reduce the forces transmitted to the ground if the frequency of excitation force is greater than 15 Hz.

The fact that railway slab track systems generally produce more noise than ballasted track, laid to the development of a “silent slab track” in the Dutch ICES by optimizing the track (Van Lier\textsuperscript{34}). In this paper the noise emissions of a newly designed slab track system with embedded rails is compared with the noise emission of existing slab track and existing ballasted track. The acoustically optimized design was an embedded less stiff rail on a stiffer suspension. A rail (SA-42) 80\textit{mm} high and 80\textit{mm} wide is used as illustrated in figure 2.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.png}
\caption{Cross-sectional view of the optimized slab track (Van Lier\textsuperscript{34})}
\end{figure}

The rail is continuously supported by a stiffer pad and asymmetrically embedded in a stiffer elastomer. The concrete plate is thinner comparing to the existing embedded slab track system and the gutters are 110\textit{mm} wide. The results of the analysis suggest that the optimized slab track emits between 4 and 6 dB less noise than ballasted track. So having in mind that the existing slab
track produces between 3 and 5 dB more noise (Van Lier\textsuperscript{34}) comparing to the ballasted track is profound that the improvement achieved in the so called “silent slab track” is significant.

Another investigation in ground vibrations conducted in 2006 (S.J Cox\textsuperscript{33}) laid to the construction of a large test rig (figure 3) based on three 2.5 m long full-scale floating slab track elements. Two 12 m rails were attached to the slab elements with different fastening systems that can provide a wide range of stiffness values. The purpose of this study is to measure the dynamic properties of a range of different floating slab and direct fixation fastening systems.

![Figure 3: The CONVURT test rig (S.J Cox\textsuperscript{33})](image)

The results show that floating slab track forms perform better between 40 and 100 Hz frequencies when fitted with soft rail fasteners (stiffness $\leq 20 \text{ kN/m}$) than with stiff fasteners (stiffness $\geq 50 \text{ kN/m}$).

A study conducted by Steenbergen, Metrikine and Esveld\textsuperscript{23} illustrates different ways to provide adequate vertical stiffness of the track system and hence to minimize the level of slab track vibrations in order to achieve very slow rate of deterioration. The most common approach to deal with this is to apply massive soil improvements. An alternative solution is to increase the bending stiffness of the slab, e.g. by applying an eccentric reinforcement. These solutions are investigated in order to reveal the consequences for the dynamic track and ground response. To assess the effectiveness of these engineering solutions a classical model of a beam on elastic half-space subject to a moving load was employed. The results suggest that an increase of the
slab stiffness is most effective for high frequencies, while soil improvement is a better solution for low frequencies. It is also found that soil improvement can result in an increased critical train velocity. A wider slab increases the slab-soil contact with result to have decreased slab displacements in the low-frequency regime. As it is stated by the authors of the paper Steenbergen, Metrikine and Esveld\textsuperscript{23}, as a most economic solution one may think of requirements of a minimum stiffness of the subsoil in relation to train passenger comfort and critical speeds, whereas the remaining part of the required stiffness can be provided by the shape-optimized slab with a maximum contact width.

The large scale of high-speed railway construction in China inevitably led to the construction of railway station buildings (waiting halls and platforms) on or under bridges. Hence the noise and vibration problems created by the train-slab track interaction on bridges become a very important issue to be investigated in a study conducted by Xin and Gao\textsuperscript{39}. Therefore, a vehicle-track-bridge couple system dynamics model is established based on multibody dynamics theory and a finite element method. The created model consists of vehicle model, track-bridge model and wheel/rail interaction model. The model tests the effectiveness of elastic materials placed under the slab (figure 4).

![Figure 4: Track layout: (a) longitudinal section and (b) lateral section (Xin and Gao\textsuperscript{39})](image)
The system dynamic responses are calculated, and the results illustrate that the application of a slab mat layer leads to significantly smaller vibrations on the bridge. It is important to point out that in low frequency range the vibrations are enlarged making this method unsuitable. The slab mat layer affects less on wheel/rail force and bridge displacements than on rail and slab displacements and it also results in rail and slab acceleration variations. The applied slab mat layer affects dominantly the bridge acceleration. Finally the authors concluded that a slab mat layer of low stiffness ($20 - 40 \, MN/m^3$) is more suitable than that of high stiffness. That does not make the low stiffness slab mat the absolutely best solution because a slab mat with very low stiffness can lead to increased displacements of rail and slab, thereby deteriorate track life and smoothness.

Since the birth of slab track systems the noise and vibrations were an important issue that needed to be controlled e.g. In a paper dating back to 1976 (P.Grootenhuis$^{27}$) it is clearly illustrated how they manage to reduce noise and vibration emissions in two specific routes of the London subway (cut-and-cover tunnel) as well as to propose a new design of a floating slab track that could be used into a bored tunnel despite its cross section area limitations (figure5).

![Figure 5: A typical section through a tunnel with a floating slab (P.Grootenhuis$^{27}$).](image_url)

Several studies have been conducted and several successful solutions have been implemented to handle the higher noise and vibration emissions. The above described studies are a small sample of the research that has been carried out which illustrate the variety of the approaches one can have in order to improve slab track noise and vibration problems. The need for further study is clear as the slab track systems develop and with the increased high-speed lines worldwide are used more and more. This need is also illustrated in the Proceedings of the Eastern Asia Society for Transportation Studies (Chang$^{38}$), in which the authors introduce the reader with the different
floating slab track applications and the noise vibration problems in slab track systems. The paper concludes, urging the need of further research in floating slab track systems to be used in the future slab track systems in Taiwan.

### 2.1.9 Transition requirements

Special attention should be given in transition areas. According to Esveld\(^5\) transition points occur in substructures between embankments, bridges and tunnels. There are also superstructure transitions between slab track and ballasted track. According to Talampekos\(^41\) transitions can be found also between embankments and culverts as well as between reinforced and unreinforced areas in a slab track system. The transitions points are the areas where the rigidity of the track shifts due to the different elastic properties between the dissimilar track structures (Talampekos\(^40\)). The transitions are able to affect the smoothness and the safety of a ride as well as to damage the superstructure of the track (Talampekos\(^40\)), in figure 6 a damaged transition area is shown.

![Figure 6: Typical differential settlement of a freight railroad ballasted track bridge approach (Read & Li\(^10\)).](Image)

The principle train response at a transition is clearly illustrated in figure 7.
The most common techniques to deal with this problem are the following:

- Equalize stiffness by a gradual decrease of the elasticity of the rail fastening (Esveld⁵).
- The application of two extra rails over a length of 20 meters. According to Talampekos⁴⁰ the extra rails should be positioned 5m on slab track and 15m on the ballasted track, see figure 8.
- Reducing settlements through stabilization of ballast by chemical binders (Esveld⁵).
- The application of a reinforced anchor at the end of the slab track in combination with a horizontal slab as buffer at the beginning of the ballasted track (Esveld⁵).
- Smoothing the stiffness/modulus step change at the interface by gradually increasing stiffness on the lower stiffness side of the transition, see figure 9.
Figure 9: Transition remedy in which the stiffness step change is modified with a gradual increase in stiffness (Read & Li10).

- Installation of a series of increasingly longer ties on the ballasted track side of the transition, as shown in figure 10. Although this is one of the simplest and older solutions an analysis using GEOTRACK Carried out by Sussan and Selig (Read & Li10) indicate that despite its larger ballast bearing area, it does little to increase the track stiffness.

Figure 10: AREMA Plan No. 913-52 approach ties for open deck bridges and trestles (Read & Li10)

- The use of geo-piers (stone columns, concrete piles, sand and timber columns) is an effective way to stabilize and strengthen weak subgrades in transitions, see figure 11.
The research results in Digest 79 (Read & Li\textsuperscript{10}) illustrate few of the most efficient transition designs for rail transit applications based on previous researches and analysis carried out by GEOTRACK analysis. Few of the most efficient enhancements as indicated in Digest 79\textsuperscript{10} are the following:

- Matching the vertical fastener stiffness of direct-fixation track, ballast deck, or open deck bridges to the track modulus and rail deflection behavior of the at-grade ballasted track, without modification of the at-grade track, provides the most efficient and cost effective design.
- The use of 10 mm concrete tie pads with a nominal stiffness of 200 to 300 kip/in (kN/m) on ballast deck bridge concrete ties provides adequate resilience to transition to ballasted track on average-stiffness subgrade.
- Subgrades with low stiffness ($E_r \leq 5$ ksi) require some modification in addition to the controlled resilience of the structure track. To modify the physical state of the soil it is necessary to install a structural reinforcing layer between the ballast and subgrade such as HMA (Hot Mix Asphalt) underlayment or a concrete approach slab.
- In new constructions, weak subgrade conditions must be avoided by careful soil selection and the application of geotechnical best practices.

Despite the numerous pre-mentioned measures that can improve functionality of transitions, there are still improvements or even new methods that have to be discovered in order to develop a safer and more comfortable railway environment in the future (Lichtberger\textsuperscript{22}).
2.1.10 Signaling systems & Electro-technical requirements

The signaling 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 hence their planning has to be completed prior to the construction of the slab track (Lichteberger\textsuperscript{23}). As stated in the UIC report\textsuperscript{15}, the ballastless track layouts have to take into account interfaces with the signaling and the overhead contact lines. It concerns mainly questions of site reservations for equipment, of electrical connections to the rail, of insulation between rails and of possible ground linkage of metallic reinforcements. These problems have to be taken into account seriously but do not play any role in the decision of the suitable slab track system. The fastening systems can ensure a safe insulation performance between rails.

2.1.11 Slab track on bridges

The application of slab track according to Esveld\textsuperscript{5} could pose problems if certain mechanical behavior is not considered. A bridge provide 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 are implemented, when slab track systems are applied in short bridges (Esveld\textsuperscript{5}):

- By reducing the clamping force in fasteners, the movements of the bridge are counterbalanced if the sleepers on top of the reinforced concrete roadbed are rigidly connected to the bridge deck or direct rail fastening systems are used.
- In bridges up to 15 m long, a continuous rail-support connected to the bridge can provide adequate rigidity.
- For spans up to 25 m, sliding slabs allow the bridge structure to move freely underneath the slab track.
- By applying a track frame concrete or concrete-asphalt roadbed, the track lies freely movable on top. This is possible due to the possible motions and twisting of the sleepers on top of the bridge structures and spans up to 10 m with frame-spans limited to 25 m.
2.1.12 Slab track in Tunnels

Most slab track constructions take place in tunnels where the ground is stiff and stable. The application of slab track in tunnels is very efficient in terms of construction, durability, strength and economy. The slab track can be built directly on the tunnel base and the thickness of the slab in many cases can be reduced compared to the slab track in earth structures (Lichtberger22). In addition, Esveld5 states that when slab track is applied in tunnels the drainage requirements, as well as vehicle access in case of calamities and safety issues, must be guaranteed. The available free space of the tunnel may influence the decision of the most appropriate slab track system.
Figure 13: *Tunnel cross-section with the required dimensions of free space* (Darr & Fiebig\textsuperscript{12})
3 Different slab track systems

The different slab track systems developed around the world are presented in this chapter. These systems are listed in table 1 and are divided in two main categories, discrete rail support systems and continuous rail support systems. Further, these two are divided in four and two subcategories respectively.

Table 1: Different slab track systems (Bastin\textsuperscript{31}, Miodrag\textsuperscript{24}, Esveld\textsuperscript{5}, Lichtberger\textsuperscript{22})

<table>
<thead>
<tr>
<th>Ballastless Track Systems</th>
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<tr>
<td><strong>Discrete Rail Support</strong></td>
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<td>WALO</td>
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</table>
3.1 Discrete rail support

When the continuous rail is attached on supporting points (usually fastened on sleepers), then the slab track system belongs to the discrete rail support category as shown in table 1.

3.1.1 Sleepers or Blocks encased in Concrete

3.1.1.1 Rheda system

The Rheda system in its various forms is one of the most commonly used slab track systems worldwide, with 400 km in Germany (Bastin\textsuperscript{31}), 150 km in Holland, 2×26 km in Taiwan, 2×28 km in Spain, 40 km trial section near Tschechien in China, 22 km in Greece (ISAP\textsuperscript{49}, ERGOSE\textsuperscript{48}), as well as two short sections in Britain and other shorter sections in various countries.

This system is widely used due to its adequate performance and long experience comparing to other slab track systems (Talampekos\textsuperscript{40}). The Rheda design is free of any patent rights, thus, since its birth it has been under continuous development by various contractors and many different structural versions have been created to fulfill different specifications in various projects.

The first Rheda system to be constructed was in the Rheda - Wiedenbruck station (Germany) in 1972 (Lichtberger\textsuperscript{22}). Despite its continuous development, all the designs are based in the original classic Rheda design preserving the following common features:

- Encased concrete sleepers
- Sleepers have the same length 2.6 m (an exception is the Rheda Berlin system which is shorter, figure 14)
- The adjustments of the track position are achieved by vertical and horizontal adjustments.
- The Rheda systems rest on a hydraulically bonded layer (HBL) 30 cm thick and a frost protection layer (FPL) approximately 50 cm thick.
- The minimum concrete quality for the concrete slab is C30/37.
- The overall heights of the various Rheda designs are between 830mm and 961 mm (rail top to the top of the FPL).

The Rheda system is very flexible allowing for design changes and enhancements in order to fit the demands of each project. Hence it can be found in tunnels, bridges, as well as on earth structures. Figure 14 illustrates the most significant design versions of the Rheda system.
Figure 14: *The most significant developed Rheda systems (Rail One*)

[Diagram of Rheda systems]
Rheda 2000

The latest developed version is Rheda 2000 as shown in figure 15. This system is flexible enough to allow for design adaptations according to the individual constraints of a project. The basic system structure, however, always consists of:

- Modified twin-block sleepers (B 355 W60M SBS) with untensioned braced girder reinforcement (filigran type) as shown in figure 15 (Lichtberger).  
- The sleepers are securely and reliably embedded in a monolithic concrete slab (Lichtberger).  
- Highly elastic rail fastenings are used to ensure the required vertical rail deflection for load distribution and for smooth train travel (Talampekos).  
- The use of rail fastening systems (vossloh 300) with a soft elastic pad 10~12 mm thick with static elasticity $C_s = 22.5 \pm 2.5$ kN/mm results in a deflection of about 1.5 mm under a static 22.5 t axle load (Bastin).  

Cross section of the rail at least UIC 60 (Kalamatas).

![Figure 15: Rheda 2000 on earthworks (Rail One)](image-url)
The goals of Rheda developments

According to Esveld\textsuperscript{5} and Rail One\textsuperscript{30} the primary goals of the Rheda system are the following:

- Uniform system architecture.
- Improvement of the monolithic quality.
- Design optimization.
- Integrated techniques for slab track installation.
• Great adaptability to all types of substructure and models executed, by means of application of cast in place concrete for the concrete track-supporting layer (Rail One\textsuperscript{30}).
• Flexible, high performance installation procedures on the basis of simple installation steps reproducible for both manual as well as automated procedures (Rail One\textsuperscript{30}).

3.1.1.2 ZÜBLIN system

The züblin slab track system development started as early as the late 1970s (Züblin\textsuperscript{46}). It is consisted of concrete twin-block or mono-block sleepers embedded in a monolithic concrete slab as shown in figure 19 and the sleepers are pushed in the fresh concrete by means of vibration (Lichtberger\textsuperscript{22}, Esveld\textsuperscript{5}). This system was developed in order to modernize the mechanical equipments of construction in order to increase the construction speed and reduce costs (Kalamatas\textsuperscript{20}). In general terms the züblin slab track system is placed on a HBL 30cm thick and a FPL 50cm thick under the HBL. The concrete bearing layer (CBL) is normally 28cm thick and 2.8m wide (Lichtberger\textsuperscript{22}), figure 20. The most recent züblin developed system as shown in figure 21 is 24 cm thick and the two individually reinforced concrete sleeper heads are connected by steel lattice trusses to form a twin-block sleeper. This developed system shown in fig 21 has been used in China in a 460km long high speed double track in 2005 (Züblin\textsuperscript{46}).

Figure 19: Züblin Design, mono-block sleeper (Lichtberger\textsuperscript{22})
Key features of Züblin design construction:

- In an eight hours shift a production of 150 to 200 m can be achieved.
- This slab track system does not require concrete troughs for controlled crack formations.
- To achieve a regular crack pattern and acceptable crack widths, the longitudinal and lateral steel reinforcing bars are placed near the bottom of the CBL.
• The züblin slab track system is made rigid in order to cope sufficiently with uncertainties that may exist regarding the bearing capacity of the subsoil.

3.1.1.3 Heitkamp system

The basic heitkamp design follows the same principles of the classic Rheda design system with concrete trough (Darr & Fiebig\textsuperscript{12}). The trough is filled with gravel instead of concrete, allowing common rail construction machines to tamper and align the rail in the predetermined position (Franz\textsuperscript{29}). After establishing the proper rail positioning, the hollow spaces in the ballast bed are poured out with a cement emulsion (Lichtberger\textsuperscript{22}). A 390 m long test section has been constructed in 1996 in Germany. The dimensions and further technical details of this design can be observed in figure 22.

![Figure 22: Cross section of the Heitkamp slab track system (Darr & Fiebig\textsuperscript{12})](image)

3.1.1.4 SBV system

The SBV slab track system has analogous construction technique to Rheda construction system. The track is placed on a supportive asphalt layer at a predetermined position and infused with mastic asphalt under and between the concrete sleepers. The only way to pour the asphalt during construction is by hand (manual labour), making the construction procedure more difficult and
time consuming. The undersides of the concrete sleepers contain a non slip profile in order to provide the necessary lateral displacement resistance, especially during summer months where asphalt warms. The SBV system is no longer used due to the development of other slab track systems using asphalt layers, which can achieve a ±2 mm precision (Darr & Fiebig12, Franz29).

3.1.1.5 Stedef, Wallo, Sonnevile-LVT systems

The stedef (French), Sonneville-LVT (Swiss) and Wallo (Swiss) slab track systems are governed by the same construction and design principles. As shown in figure 23, a resilient pad is placed under the sleeper and then encased in a rubber boot providing high flexibility and reassures high protection against noise and vibrations.

![Figure 23: (a) Sleeper of the Sonneville-LVT system, (b) Systems with elastically encased sleepers / supporting blocks, poured into an in-situ concrete track slab (Sonneville\textsuperscript{35}, Kalamatas\textsuperscript{20})](image)

The construction principle used in these systems, is called “Top/Down”. This building method consists, after installation of sleepers and rails and regulating of geometry, to pour in situ an infill concrete between the supporting structure and the rubber boot (UIC report\textsuperscript{15}). One sensitive area of those systems is the possible erosion can caused by water. It is possible to have water infiltration from the rubber boot making the sleepers loosen, not stabilized and firm as before (Kalamatas\textsuperscript{20}). On the other side their big advantage is the easy exchange of sleepers and every supporting point (resilient pad, rubber boot etc.). The simple construction method and the easy-
flexible maintenance capabilities of these systems make them a very competitive solution with result to be widely used worldwide (Kalamatas\textsuperscript{20}).

**Stedef**

The Stedef system has been constructed in several countries around the world, it is approximately estimated that 200 km (51 km, Athens metro) at least have been constructed only in Europe (UIC report\textsuperscript{15}, ATTIKO METRO\textsuperscript{1}). This system is mainly used in tunnels and the rail fastening which traditionally have been used is Nabla. In figure 24 is illustrated a classical Stedef system. The most recent development of the Stedef system is the Sateba S312 shown in figure 25. This development brought two improvements:

1. It makes possible the repair of a damage caused after a derailment or material failure having reduced the possibility of total replacement of the sleeper without being necessary to replace the wedging concrete.
2. It is provided with a polyurethane waterproof seal preventing the water to infiltrate from the edges of the rubber boot.

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![Cross-section of the Stedef slab track system](image)

**Figure 24:** *Cross section of the Stedef slab track system* (Darr & Fiebig\textsuperscript{12}).
Figure 25: *Classical and recent developed Sateba S312 Stedef System (UIC report)*

**Sonneville-LVT**

All the technical details for the Sonneville-LVT system are illustrated in figures 26 and 27. As mentioned earlier, this system is very similar to Stedef as well as Wallo systems using a rubber boot as shown in figure 23 (Esveld⁵). The fastenings that have been used for this system are Vossloh W14, Pandrol e-clip or fastclip and Sonneville S.75 (Sonneville³⁵). This system is one of the oldest and most used around the world, having 1031 km of LVT constructed tracks in total. One of the most significant LVT constructions worldwide is the Channel tunnel (France – England) 100 km double track.

Figure 26: *Sonneville track used in the Eurotunnel (Bilow, Gene & Randich)*
The latest version of the Sonnevile-LVT system is called LVT high attenuation and it has larger blocks and softer resilient pads for higher demands of noise and vibration attenuation, see figure 27. These two characteristics result in a lower natural frequency of the system that lies in the range of floating slabs (Sonneville\textsuperscript{35}). The LVT system offer a lower profile version if needed, see figure 27.

Figure 27: Standard and High Attenuation LVT systems, standard and low LVT profile (Sonneville\textsuperscript{35})

**Walo**

Walo is a Swiss developed twin block variant related slab track system pretty similar to Stedef and Sonneville-LVT. The similarities of this system can be observed in figure 28.
3.1.2 Sleepers on Top of Asphalt-Concrete layer

Results have shown that these systems perform adequately and that asphalt layers can provide a stable and supportive layer suitable to replace the conventional ballast layer. Due to the asphalt properties, these systems can perform slight plastic adaptations when it is needed. According to Esveld\textsuperscript{5}, when higher pressures occur below certain sleepers than below others, asphalt will deform because of its visco-elastic properties until a new equilibrium has been established leaving the pressures more leveled. Few more positive features of these systems are that allow exchange of sleepers in case of damage and generally are easily maintained.

3.1.2.1 ATD system

The ATD system consists of an asphalt roadbed set up over the cement stabilized support layer (HBL) (Darr & Fiebig\textsuperscript{12}). The sleepers are placed on the asphalt layer and the ridge in the middle of track between them takes up the lateral forces (Lichtberger\textsuperscript{22}). After the track grid horizontal adjustments, the free space between the ridge and the sleepers is cast in a synthetic material. The construction of these includes the use of twin-block as well as mono-block sleepers which are equipped with a groove on their lower surface which can resist all the lateral forces (Lichtberger\textsuperscript{22}, Esveld\textsuperscript{5}), see figure 30,a. The ATD system as shown in figure 29 is consisted by the following basic elements (Franz\textsuperscript{29}):

- Hydraulically-bonded Layer (HBL).
- Asphalt Supportive Layer (ABL or ASL).
- Twin-block sleeper B350W60 or mono-block sleeper B320W54.
- Elastic rail fastenings and the UIC 60 rail.
To provide extra support and greater resistance of the sleepers to survive sudden breakings of the continuous welded rail, ballast is placed around the sleepers or heavier sleepers maybe used (UIC report\textsuperscript{15}). According to Esveld\textsuperscript{5}, the asphalt is applied with ±2 mm accuracy and is laid in three or even four different layers (figure 29). The asphalt mix can guarantee a 50 to 60 year life span under extreme weather conditions.
3.1.2.2 BTD System

The BTD system consists of mono-block sleepers only placed on a concrete supporting layer (CBL). Every second sleeper is plugged in the concrete bearing layer (CBL) by a steel dowel (Lichtberger\textsuperscript{22}). There are two versions of construction developed which differ in their transfer of lateral forces (Darr & Fiebig\textsuperscript{12}):

- Version 1 (V1), clamp fastening with a clip glove at the sleeper midpoint of every second sleeper as shown in figure 31 (Franz\textsuperscript{29}).
- Version 2 (V2), steel plugs through a hole at the sleeper midpoint of every second sleeper as shown in figure 31 (Franz\textsuperscript{29}).

![Figure 31: BTD construction, version 1 (V1) and version 2 (V2) (Darr & Fiebig\textsuperscript{12}, Franz\textsuperscript{29}).](image)

In V1 the clip glove is clamped in a pre-finished guided groove after the rail span adjustments. This version 1 is no longer used according to (Darr & Fiebig\textsuperscript{12}). After adjusting the rail span a hole is drilled in the concrete bearing layer (CBL) through the hole in the middle of the sleeper, and then a steel plug is bracing the sleeper with the concrete bearing layer (CBL) (Darr & Fiebig\textsuperscript{12}).
3.1.2.3 Walter

The Walter slab track system follows the same design and production principles of BTD (V2) system. The main difference between these two systems is that Walter system uses an asphalt supportive layer (ASL) instead of concrete supportive layer (CBL). The mono-block sleeper is firmly connected to the lower asphalt layer (ASL) by a steel anchor rod crossing the sleeper as shown in figure 32 (Darr & Fiebig\textsuperscript{12}, Franz\textsuperscript{29}).

![Figure 32: Walter slab track system construction (Darr & Fiebig\textsuperscript{12})](image)

3.1.2.4 Sato system

The Sato system is consisted of Y-steel sleepers anchored on an asphalt supporting layer by welding the sleepers to a flat steel surface in the asphalt rail span using the so called Nelson anchors so that the sleepers are fastened in both vertical and horizontal direction as it is illustrated in figure 33 (Lichteberger\textsuperscript{22}). This rather complicate and expensive solution was further developed to other construction types known as FFYS and FFBS-ATS-SATO (Franz\textsuperscript{29}).
3.1.2.5 FFYS system

This system was primarily designed to provide excellent position stability, reduction of costs due to the fast and easy installation procedure and good recycling resources. The Y-sleepers of this system is a good solution for new tracks, renewals and expansions as well as for normal, wide, narrow and multi-track sections. It can also be used for special switch design in slab tracks or on ballast tracks. This modern steel sleeper is created from two s-shaped, heat-molten wide flange supports and two same straight girder sections. Two lower and six upper cross brackets welded to the flanges are used to connect the steel profiles (Franz29). The dimensions and other design details of the FFYS system are depicted in figure 34.

The Y-steel sleepers in contrast to conventional shaped sleepers have the following differences (Franz29):
• Y – bracket shape.
• Double support for rails.
• Three rail support areas per sleeper.
• Basic body casting made of supportive girder profiles.

The above stated differences can be observed in figure 35.

Figure 35: *Section and top view of Y-sleeper* (Franz29).

The advantages of the Y-sleeper design are the following (Franz29):

• Higher than the average life span.
• Cheap comparing to its high structural stability.
• 30% less ballast required
• Half demand of sleeper reduction in comparison to normal shaped sleepers.
• Sleepers almost completely recyclable.
• Double support of the rail allows for smoother vehicle running and less wear.
• Less tamping effort due to the larger tamping intervals.
3.1.2.6 FFBS-ATS-SATO

The FFBS-ATS-SATO system is shown in figure 36 and it was built in Germany as a trial version (390m) for tests. It is supported by an asphalt layer and has concrete sleepers with A8 support points being used. The transfer of lateral is compensated in a similar way as in the FFYS system using web plate on the sleeper undersides. The sleepers are poured in special grooves cut into the asphalt supporting layer (Franz29).

![Figure 36: FFBS-ATS-SATO slab track system (Darr & Fiebig12)]

3.1.2.7 Getrac system

This slab track system is the most recent, developed in 2003 in Germany (Rose, Texeira & Ridgway18). It consists of an asphalt support layer and pre-stressed concrete sleepers laid and anchored on it. The plug used to keep the sleepers tight on the asphalt is specially designed to easily transfer the lateral and longitudinal forces into the asphalt layer. The heavy weight of the rail span (sleeper B316 weigh 380kg) can compensate the vertical forces altering the rail due to the “lead wave” (Franz29). The Getrac slab track system has two different versions, A1 and A3 (Franz29). The A1 design shown in figure 37 has a 2.6m long concrete sleeper and it is used in projects without any space restrictions. The A3 design shown in figure 38 has a 2.4m long sleeper which is slightly wider; hence it is suitable for projects with space restrictions such as narrow tunnels (Rose, Texeira & Ridgway18). The sleepers of the A3 design have larger bearing surface that reduces the contact pressure between the sleeper and the asphalt. This allow for a
5cm reduction of the asphalt supportive layer thickness, making it more suitable for upgrading existing narrow tunnels by providing extra free space.

Figure 37: Getrac A1 slab track design (Darr & Fiebig\textsuperscript{12}, Lichtberger\textsuperscript{22}, and Franz\textsuperscript{29})

Figure 38: Getrac A3 slab track design (SSF\textsuperscript{36})

The construction sequence of the Getrac system is the following, see also figure 39:

- A paving machine is laying the hydraulically bonded layer (HBL) (Franz\textsuperscript{29}).
- An automatically – controlled, cable guided high performance paver installs the ASL in two or three layers (Franz\textsuperscript{29}).
- The last asphalt layer or covering layer is made of 0/8 asphalt adjusted to the dimensions of the anchor blocks with a high precision of ±2mm (Franz\textsuperscript{29}).
• The cylindrical anchor block (figure 37 and 39) is surrounded by an elastic compound (rubber) and it is half embedded to the fresh asphalt layer (Kalamatas\textsuperscript{20}).
• Installation of the rail span (UIC 60) and B316 steel-reinforced concrete sleepers with vossloh system 300-1 rail fastening (Franz\textsuperscript{29}).

Figure 39: Getrac construction, a. Paving with asphalt, b. Installation of concrete sleepers, c. Concrete anchor block, d. Finished Getrac A3 at Brandleite tunnel (Rose, Texeira & Ridgway\textsuperscript{18}).

The advantages of this system are listed below (Rose, Texeira & Ridgway\textsuperscript{18}):

• Good geometrical structural ability to maintain proper geometric alignment.
• Designed to cope with high speed and heavy goods trains.
• Easy and quick installation.
• Long life cycles with minimum maintenance.
• Easy and fast track renewal after train accidents.
• Cost-effective.
• High design flexibility by reducing the cross sectional thickness or/and the overall width of the track.
3.1.3 Prefabricated concrete slabs

This slab track category is consisted by reinforced or pre-stressed concrete slabs preserving constant and safe the inclination and gauge of the two lines of rails simultaneously (UIC report\textsuperscript{15}). Prefabricated slabs can be found in many places around the world, e.g. Japan, Germany, Italy, China and Taiwan.

The advantages of this system are the following (Esveld\textsuperscript{5}):

- High quality of the prefabricated slab components.
- High level of mechanization, hence fast construction.
- Labour-saving construction at site.
- Direct adjustment and fixation of the rail.
- Very low risk of failing workmanship.
- Repair and renovation friendly.

Their disadvantages are their considerable higher structure (Esveld\textsuperscript{5}), and most importantly their high cost which according to Lichtberger\textsuperscript{20} is in many cases four times more than in ballasted track.

3.1.3.1 Shinkansen system

This slab track system was first developed and used in Japan in 1972 (Lichtberger\textsuperscript{22}). It consists of a sub-layer stabilized with cement, and assembly plates of 4.95m × 2.34m × 0.19m and 0.16 m thick in tunnels with low pretension are used in longitudinal and lateral dimension (Esveld\textsuperscript{5}, Lichtberger\textsuperscript{22}). These slabs weigh approximately 5 tons each and are adjusted on top of a hydraulically bonded surface (HBL), under the slab is injected a minimum 4 cm thick bituminous mortar, except few cases where a rubber mat in some antivibration versions is used (UIC report\textsuperscript{15}, Esveld\textsuperscript{5}). The slabs are hold longitudinally and laterally by concrete cylinders (dowel) which are rigidly connected with the structural concrete of the bearing plate (Lichtberger\textsuperscript{20}). Details on the shinkansen slab track system can be observed in figure 40.
Special attention must be paid in the bituminous injection under the prefabricated slab due to its weakness in fulfilling the expected technical performance. It has been proved in the past to be weak in frost; hence there are two composition types to be used according to the meteorological conditions of the site (Lichtberger\textsuperscript{22}, UIC report\textsuperscript{15}).

The Shinkansen slab track system has influenced other systems that have been used around the world, using similar design and construction principles. Few of them are the slab track system used to connect Seoul to the Port of Pusan in South Korea, the IPA design in Italy which is heavily influenced from the Shinkansen track (Esveld\textsuperscript{6}), as well as the 345 km long high speed line in Taiwan which incorporates all the basic features of the Shinkansen track (Bastin\textsuperscript{31}).

The development of this system incorporate slabs with hollows in the middle (frame-shaped track) as shown in figure 40, to optimize the setting up of the bituminous mortar as well as to save material and make the slab lighter (UIC report\textsuperscript{15}). According to Bastin\textsuperscript{31} the most recent Shinkansen designs are slightly thicker, at 220mm, and have a $2860 \times 800$ mm ‘void’ between the rails. The slabs are made lighter resulting to a more effective grouting operation. In figure 42 is shown a real example of the Japanese Shinkansen slab track system.
The construction method for Shinkansen track (Esveld⁵)

The installation method of the Shinkansen system used in Hokuriku Shinkansen is illustrated in figure 43 and is called the “moving plant on running rail method”. This method has been confirmed to be the most fastest and efficient for laying the track in long lengths in one direction.

The construction procedures:

- The 200m long rails are welded in the depot.
- The rails are transferred in the site and laid on trolleys.
- The trolleys are driven by a running motor on the temporarily laid rails with a gauge of 1435mm.
- The temporarily laid rails help to follow the slabs as they are being placed into position as well as to inject CA mortar under the slab in a neighboring line. These temporary lines are used on the completed line too. The rails are laid on the neighboring track.
- The slabs are transported to the site and laid by widening the rail gauge to 3000mm.
Since the 3000mm gauge is used to transport slabs from the trolleys onto the rails laid at the location of the trolleys using additional rails for a 75m long section.

The moving plant running on rails with a gauge 1435mm is creating CA mortar at the site and transfers it onto the neighboring track.

When the CA mortar has gain strength under the slab, the rails are positioned and fastened with normal fastening devices.

Using this method a 200 to 280 m of Shinkansen slab track can be constructed per day. A schematic representation of this construction method is illustrated in figure 43 below.

3.1.3.2 Bögl system

The Bögl slab track system was developed and first used in Germany in 1977 (Bastin31). This prefabricated system is made of steel fiber concrete (B55 or C45/55) plates 20cm thick, 6.45 m long and 2.55 or 2.80 m wide, having a total construction depth of 475 mm as shown in figure 45 (Esveld5, Bastin31, Lichtberger22). The plates are laterally prestressed and longitudinally normally reinforced by the so called ‘GEWI’ bars (see figure 44) (Bastin31). These prefabricated
slabs are designed with special breaking points arranged between the supporting points in order to prevent random crack formation in the slab (Lichtberger\textsuperscript{22}). This design is turned to be a system of many wide sleepers joined together due to these specifically designed cracking points. Special screw-jacks (spindles) (see figure 45) integrated in the slabs reassure an easy and fast adjustment of the plates (Esveld\textsuperscript{5}).

**Figure 44:** *Max-Bögl track system* (Bastin\textsuperscript{31})

**Figure 45:** *Geometrical characteristics of the Bögl concrete slab* (Kalamatas\textsuperscript{20})
The standard procedure of construction, according to Bastin\textsuperscript{31} is as follows:

1. The frost protection layer (FPL) is laid.
2. A paver machine is constructing the hydraulically bonded layer (HBL). Tolerance ±5mm, target ±2mm.
3. Positioning of the slabs (see figure 46) with 50 mm nominal joint between them. Accuracy ±10 mm.
4. Adjustment of slabs (fine lined and leveled) with the assistance of the screw-jack mechanisms.
5. Outer edges sealed with mortar.
6. Injection of the bitumen/cement grout through special holes along the slab longitudinal centre line (see figure 44).
7. Narrow joints filled with mortar (see figure 45 the opening for the grout).
8. The longitudinal reinforcement (GEWI bars) joined and stressed together with turnbuckles.
9. The slab track structure is completed after the wide joints are filled with mortar.
10. The 120m long-welded rail is unloaded and placed onto baseplates.
11. The rails are distressed after the rails are welded together to create a continuously welded rail.

Figure 46: Positioning of the Bögl slabs
Figure 47: Nürnberg – Ingolstadt: one Bögl track completed (Bastin31)

The main advantages and disadvantages of this system, according to Bastin31 are the following:

**Advantages**

- Manufacturing in factory reassures excellent quality.
- Easy and fast to install.
- Once installed can be opened to traffic.
- Easy to replace damaged parts or whole units if needed.

**Disadvantages**

- Mainly the costs of the system, which rely a lot in the distance of the site and the factory. A unit weighs approximately 10 tones; hence a highway lorry can carry only three slabs per delivery. If the distance is great then the cost of this system may be extravagant, hence an alternative more cost effective slab track system may be more suitable.

3.1.3.3 ÖBB-Porr system

The ÖBB-Porr system was developed in Austria and it was first constructed as a test track (450m) in 1989 (UIC report15). This system as shown in figure 48 consists of slabs on elastic support of 5.16 m × 2.4 m × 0.16 to 0.24 m with a two resilient level fastening system type IOARV 300 (UIC report15, Lichtberger22). The assembly reinforced concrete plates are adjusted on a hydraulically bonded bearing layer (HBL) or a concrete tunnel sole by the use of spindles and then sealed by concrete (Lichtberger22). The plates present two central rectangular openings of 0.91 m × 0.64 m to assist the setting up of the wedging mortar as well as to take all the horizontal efforts (Lichtberger22). All the slab surfaces which are in contact with the sealing concrete are coated with a resilient polyurethane-cement layer (rubber granular mix) with a 2.5-3mm thickness as shown in figure 48 (Lichtberger22, UIC report15). After this cemented rubber
granular mix is applied, a conical shaped concrete plug is made at the rectangular openings of the slab to prevent uplifting of the slab (UIC report\textsuperscript{15}). This separation layer ensures that the plates are decoupled from vibrations as well as that it separates the slabs from the sealing concrete making the replacement of the slabs easier when they are damaged (Lichtberger\textsuperscript{22}). The standard ÖBB-Porr design system can be considered as a mass-and-spring system with a mass of 1 tone per linear meter with many advantages against vibrations (UIC report\textsuperscript{15}).

![Figure 48: ÖBB-Porr slab track system (Darr & Fiebig\textsuperscript{12})](image)

### 3.1.3.4 IPA slab track system

This system was developed in Italy and used for first time in 1984 (Round\textsuperscript{8}, UIC report\textsuperscript{15}). It is very similar to the Shinkansen system since it was the outcome of a co-operation and technology transfer from the Japanese National Railways (Round\textsuperscript{8}). It consists of prefabricated prestressed concrete slabs set in cement/asphalt mortar on a concrete bearing layer. The main difference between IPA and Shinkansen design is that the locating post for providing longitudinal and lateral fixing of the slabs, form part of the slabs with the recess being made in the concrete base (Round\textsuperscript{8}). In figure 49 the reader can find all the information about its dimensions and structural features.
3.1.4 Monolithic Designs

These designs are consisted of only a continuous monolithic concrete layer and direct rail fastenings adjusted on it. The sleeperless designs are established either as monolithic concrete layer produced by a concrete paver or as prefabricated slabs connected together (Esveld\textsuperscript{5}, Lichtberger\textsuperscript{22}). The direct rail fastenings used for this system are very effective in bridges making them lighter and eliminate problems associating the sleepers (Esveld\textsuperscript{5}). The monolithic designs are stiff and rigid enough to behave structurally as a continuous supported elastic beam under traffic loading. The rigidity of this system makes it suitable for use in soft soils. The loads are distributed across a much longer and wider area (Esveld\textsuperscript{5}). Attention must be paid to the crack formation of the concrete bearing layer (CBL) and proper measures have to be taken to prevent cracking caused by the rail fastenings.
3.1.4.1 Lawn Track or RASENGLEIS system

The Lawn track system consists of a water permeable concrete slab 30 cm thick and two longitudinal reinforced concrete beams of trapezoidal shape (cross section) which are connected onto the concrete bearing layer which supports and reassure the stability of the track (Lichtberger\textsuperscript{22}, Franz\textsuperscript{29}). Anchoring ties connect the longitudinal concrete beams and the concrete supporting layer (CBL) as shown in figure 51. The rail fastenings are fastened onto the longitudinal concrete beams by rail clamps cast in pre-drilled holes. The space between the concrete beams and their outer areas is filled with a substrate covered by oligotrophic grass (low vegetation) (Lichtberger\textsuperscript{22}).
3.1.4.2  FFC slab track system

The FFC (Feste Fahrbahn Crailsheim) slab track system is manufactured with high precision in preparation and installation. The supporting points (dowels) for the rail fastening system either are “shaken into” the fresh concrete during installation, or they may be inserted and glued in pre-drilled holes into the dried concrete slab (Franz26). After the dowels are inserted the rail fastening system IOARV300 is positioned at the manufacturing stage as a profile in the form of an infinitive length concrete sleeper in the concrete bearing layer (CBL) (Lichtberger22, Franz29, UIC report15). The concrete slab is made by a slipform paver and the fastening system is adjusted by a special machine following behind. The concrete base is normally 2.4 m wide as shown in figure 52, but it can reach a maximum of 3.2 m length according to Franz29. Every third support point a notch is made in order to control crack formation and to let the water to let the rain water to run off.

![Figure 52: FCC slab track design (Darr & Fiebig12)](image)

3.1.4.3  Hochtief/SHRECK-MIEVES/LONGO

The Hochtief system consists of a concrete bearing layer over the hydraulically bonded layer (HBL) and it uses concrete-embedded rail support points for rail fastening type 300 (UIC report15, Franz29). Four linking anchors are jiggled into the fresh concrete of the CBL for each individual support. Then each rail support is adjusted using a setting frame for accurate leveling and height adjustment (Mörscher25). The use of steel fiber concrete in segments revealed fissure structures with almost invisible cracking (Franz29). The surface of the concrete bearing layer
(CBL) has been designed with inclination to directly drain off the rain water (Mörscher\textsuperscript{25}). The exact dimensions and design characteristics of this system are illustrated in figure 53.

![Figure 53: Hochtief/SHRECK-MIEVES/LONGO slab track system (Darr & Fiebig\textsuperscript{12})](image)

### 3.1.4.4 BES system

The BES slab track system is consisted by a reinforced concrete bearing layer (CBL) with individual support points over the cement stabilized layer (HBL) (UIC report\textsuperscript{15}, Franz\textsuperscript{29}). This system was developed in Germany and uses the same process as the FFC in producing the form of the rail fastening at the installation of the CBL. The plugs for the rail screws are glued into pre-drilled holes in the dried concrete supportive layer (Franz\textsuperscript{29}).

![Figure 54: BES slab track system (Darr & Fiebig\textsuperscript{12})](image)
3.1.4.5 BTE slab track system

The BTE system is a concrete supportive layer (CBL) with individual support points over a hydraulically bonded layer (HBL), very similar to BES system. A two-level plate machine system is used to achieve the desirable geometry of the concrete slab layer (CBL) (UIC report\textsuperscript{15}). Two different rail fastenings have been used for this system, Ioarg 336 and ERL (BWG). The concrete areas, where the rail fasteners are located, are manufactured with extra strength. Details of the BTE design system are shown in figure 55.

![Figure 55: BTE slab track system (Darr & Fiebig\textsuperscript{12})](image)

3.1.4.6 PACT system

The PACT slab track system was developed in Britain and first constructed in 1969 at Radcliffe for testing purposes (Round\textsuperscript{8}). It is consisted of a continuous paved unreinforced concrete layer on which a paved, profiled continuous reinforced track slab is based (Bastin\textsuperscript{31}). The connection between these two layers is achieved by shear links in the reinforcement of the upper slab (Round\textsuperscript{8}). This system has a 22.9 cm thick concrete slab that is 2.43 m wide (Canadian Pacific Railway) (Bilow, Gene & Randich\textsuperscript{9}). After the curing of concrete is complete, holes are drilled (diamond-core) and the continuous welded rail is laid on a continuous rail pad and fixed to inserts embedded in the slab (Bilow, Gene & Randich\textsuperscript{9}, Bastin\textsuperscript{31}). Although it was designed for high speed lines, this has not happened. It has mainly used in tunnels (wet tunnels) because of its low construction height and low maintenance needs comparing to ballasted track. The maximum speed in a PACT system nowadays does not exceed the 150 km/h (Round\textsuperscript{8}). Although this system was at the forefront of slab track development, the lack of any significant new
construction in Britain did not allow for many further developments. The PACT system is out-
dated for the current standards and high speed train demands (Bastin). The advantages of this
system are the low construction costs and the high quality geometry. The disadvantages are, that
requires special laying equipment, the out-dated construction method (bottom-up) combined with
the continuous support of the rail make it harder to achieve the levels of accuracy required for
high speed, as well as that the drainage is often hindered resulting to debris collection which lead
to corrosion of the railway fastenings (Round, Bastin). The exact dimensions and structural
features of the PACT system are schematically illustrated in figure 56.

Figure 56: PACT slab track system (* Depth D at real seat varies: typically 150-250 mm.
Similarly depth of the base slab varies depending on site conditions: 300mm minimum)
(Bastin).

3.2 Continuous Rail Support

When the continuous rail is continuously elastically supported by the concrete bearing layer
either embedded or clamped then it belongs to the continuous rail support systems as shown in
table 1.
3.2.1 Embedded Rail Structures

According to Esveld⁵ the embedded rail structure (ERS) is a continuous elastically supported rail by means of a compound such as cork and polyurethane. The rail fixation is established by an elastic compound surrounding the whole rail profile except the rail head. This system includes the full range from high-speed tracks to light rail. What characterizes this concept is the absence of additional components to secure track gauge.

The characteristic principles of the rail fixation in this concept are the following (Esveld⁵):

- An elastic strip provides continuous support under the rail.
- The rail is guided in a groove by elastic fixation.
- Top-down alignment of the rail.
- The rail profile is fixed by an elastic compound.
- Optimization of the elastic compounds, the groove dimensions and strips for specific elasticity.

The advantages of this concept are the following (Esveld⁵):

- Absence of dynamic forces due to secondary bending between single rail points.
- Less noise emissions.
- Increases rail life span.
- Overall reduction of maintenance.
- The embedded rail construction height can be reduced e.g. in case of road crossing where a smooth obstacle free surface is needed.

3.2.1.1 INFUNDO-EDILON system

The INFUNDO and EDILON designs are the same type sharing the same construction characteristics and principles. The INFUNDO is the further development of the Dutch Edilon design (Franz²⁹, Lichtberger²²). This system was first developed in Netherlands in 1970’s (1976, near Deurne, testing track with speeds up to 160 km), and its development continues until our days (Esveld⁵). A continuous rail is continuously supported by elastic compounds in a groove. A concrete supportive layer is laid by a slipform paver. This layer is 40 cm thick and 2.4 m wide. The construction under the concrete bearing layer is kept the same (HBL and FPL under the CBL) as in most slab track systems as shown in figure 57 (Franz²⁹). The horizontal and vertical
forces are compensated by the cork underpad and the elastic two-component mass surrounding
the rail. The INFUNDO design is intended mainly for urban passenger rails (subways, tramways)
(Esveld5).

![Diagram of Embedded rail construction INFUNDO](image)

**Figure 57: Embedded rail construction INFUNDO (Esveld⁴)**

The concrete groove must be accurately constructed because it determines the rail height,
direction, track gauge and tilting (Franz²⁹). After the concrete trough is dried a U-shaped steel
profile is inserted (figure 58) to case in the:

- The underpad.
- The rail.
- Elastic components which keep the rail in place.

![Diagram of Details of embedded rail structure](image)

**Figure 58: Details of embedded rail structure (Esveld⁴)**
The advantages of this system are the followings (Franz):

- Reduced wear of rail allow for use of weaker rail profile.
- Low noise emissions.
- Minimization of components used.
- Fast construction.
- Good solution for combined surfaces (crossings, etc).

A new development in this system led to a lower-noise design by replacing the UIC 54 rail with the SA 42 rail as shown in figure 59. This rail can carry 225 kN axle loads and produce 5dB less noise. One more advantage of this development is the reduction of the polyurethane used due to the smaller groove size (Esveld).

![Figure 59: Low noise track design (Esveld)](image)

### 3.2.1.2 BBERS design

This system was developed by Balfour Beatty in 2000 and successfully first installed at Medina el Campo (Spain) in 2002. This system shares exactly the same construction principles as INFUNDO. The difference is the smaller rectangular rail (BB14072) which has resulted to a much smaller groove and the different rail elastic support elements. The BBERS uses, a U-shaped continuous pulltruted glass reinforced plastic shell, a U-shaped pad (micro cellular polyurethane) to fit both the shell and the rectangular rail (139.7 × 69.85 mm, advance track design) with a standard rail head profile (removable rail, 74 kg/m) as show in figure 60 (Balfour beatty).
The installation steps of the rail are the following (Penny³):

- A pulltruded glass reinforced plastic box is permanently installed in the concrete trough (a special ‘lid’ is helping for accurate positioning of the plastic box). Tolerance ± 1mm.
- The base of the shell is permanently grouted.
- The box ‘lid’ is removed and the pad and rail are inserted.

The construction of this system can be carried out by three different methods, slip forming method, pre-cast concrete, cast in-situ. The steps of each method are as follows (Balfour beatty²):

**Slip forming**

1. Take up existing track
2. Excavate and/or prepare formation depending on ground conditions
3. Place lean mix base for slab if required by design
4. Place reinforcement
5. Slip form
6. Align and fix sub system (shell and pad)
7. Grout shell into final position
8. Distribute rails
9. Weld and install rails
Pre-cast concrete slabs

1. Take up existing track
2. Excavate and/or prepare formation depending on ground conditions
3. Lay slabs
4. Jack, align and grout slabs into final position
5. Join slabs
6. Distribute rails
7. Weld and install rails

Cast in-situ

1. Take up existing track
2. Excavate and/or prepare formation depending on ground conditions
3. Place lean mix base for slab if required by design
4. Place reinforcement
5. Erect shuttering
6. Pour concrete
7. Strike formwork
8. Align and fix sub system (shell and pad)
9. Grout shell into final position
10. Distribute rails
11. Weld and install rails

3.2.1.3 Deck-Track design

As stated by Esveld\(^5\) the Deck-Track is a system of high flexural stiffness which can be applied in soft soils. It was developed in Netherlands and a 200 m test track has been constructed in Rotterdam. It consists of a continuous in-situ or prefabricated concrete bearer (concrete frame structure) laid into the ground as shown in figure 61. The rails can either embedded (possible use of the rail profile SA 42 for low noise emissions is possible) or directly fixed on the concrete surface. Deck-Track is a concrete ‘hollow tube’ nearly the same weight of the removed soil. Its high bending and torsional stiffness result to reduced vibrations. This help to avoid differential settlements providing a stable basis for track even on soft soils. Deck-Track acts like a bridge surpassing problems associated with weak spots in the soil.
3.2.2  Clamped and continuously supported rail

These systems provide continuous support of the rail by clamping the web of the rail.

3.2.2.1  Cocon Track system

This system is specially designed for tramways and consists of a combined transverse and longitudinal concrete sleeper, as shown in figure 62, using conventional fasteners supporting the rail. The fasteners are placed on the crossings of the H-shaped sleeper having a 1200 mm distance among them. This system is designed for curves $R>20$ m. The rail sit on a two layer strip, the first layer is soft and when the rail is fastened, it will be compressed and lose 40% of its thickness (adaptation rail), the second rail is stiff to bear with the loads. Together with the CDM-strip a cork/rubber elastomer is applied between the fastener springs and rails to prevent direct contact (see figure 62). The rail is encased in a high quality recycled rubber chamber helping to avoid contact between rail and asphalt or concrete (Esveld\textsuperscript{5}).
3.2.2.2 Grooved rail system

This slab track system is a continuously supported grooved rail (ERL) developed by Phoenix mainly for tramways. It is consisted of an elastically supported rail with or without rail fasteners. The elastic support underneath the rail (see figure 63) is a rubber strip with air chambers. The rail is encased in special rubber chambers as shown in figure 64 to reduce the noise emissions and to work as a transition between the rail and the road asphalt. A high grade concrete bearing layer (CBL) provides support to both rails on it which are connected to each other with steel bars (see figure 64) to secure the track gauge.
3.2.2.3 Vanguard & KES designs

The Vanguard and KES systems are new designs made from Pandrol and Phoenix respectively. These systems are using the traditional concrete supportive slab to apply rail fastenings on it providing continuous support by elastic wedges or strips attached at the web surface of the rail. The Vanguard system leaves the rail base hanging unsupported as shown in figure 65. The elastic compound is held in place by side brackets which are fastened on the concrete bearing layer (CBL). The big difference with conventional fastening systems is that these fastenings allow much greater vertical deflections without an unacceptable accompanying degree of rail roll. Furthermore, this feature improves attenuation of the dynamic forces generated at the wheel/rail interface resulting to less dynamic force transmissions to the surroundings. The Vanguard system is designed for tunnels in urban areas where the vibrations pose an issue.

Figure 65: Impression of the Vanguard design (Esveld5)
The KES system was developed in 1990’s for light rail and it has been used in Germany. This system in contrast to Vanguard provides continuous elastic support in the whole surface of the rail. It shares similar construction principles with the ERL system (pg.60), but steel or concrete profiles are bolted in order to continuously press the elastomeric strips in place (see figure 66). The KES design requires more material and more accurate installation comparing to Vanguard (Esveld⁵).

![Figure 66: KES system under testing (Esveld⁵)](image)

3.2.2.4 SFF system

The SFF (vibration damped slab track) system consists of profiled trough embedded longitudinal sleepers in the concrete bearing layer (CBL). Continuous support is provided by a rubber pack which surrounds the rail (see figure 67). The sleepers are braced in the groove with profiled concrete assembly elements using screwed connections. The rail is supported by the elastic compounds below the rail head and hangs freely above the trough bottom allowing for significant vertical deflections (absorbing vibrations). The rubber used to keep the rail in place lies tightly against the rail and concrete surface acting as a seal. Any water penetrating in is collected and guided out below the rail foot through lateral holes. This system is limited to tunnels and in urban rail systems (Lichtberger²², Franz²⁹).
3.2.2.5 SAARGUMMI design

The SAARGUMMI design uses profile-free longitudinal sleepers in a trough. It is up to the user whether the longitudinal sleepers are laid on or inserted in the concrete bearing layer (CBL). The rails are continuously supported by elastomeric elements covering the rail flange and aligned using profiled clamping bodies with adjustable threaded bolts as shown in figure 68. The height and lateral position and track gauge as well as gradient of the rail are adjusted in the longitudinal sleepers.
4 Comparison of Slab Track Systems

This chapter highlights important differences between the slab track systems in terms of structural stability, flexural stiffness, structure height, noise production, speeds, maintenance need, construction costs, construction speed, and lengths of constructed tracks. It is essential to know these differences in order to realise which slab track design meets the required needs. There is no slab track system suitable for all cases; hence a good knowledge of each system characteristics is the only way to make the best possible decision.

4.1 Structural Characteristics

The superstructure of each slab track system has different flexural stiffness, these is illustrated in table 2. The various slab track systems used today are divided in six different categories as shown in table 2. One can refer table 1 to associate a specific slab track system with one of the six categories. Slab track constructions with low flexural stiffness can scarcely resist bending forces, the system rely completely on the bearing capacity and stiffness of the soil. 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 (Esveld5).

Table 2: Approximate superstructure flexural stiffness for different track systems (Esveld5).

<table>
<thead>
<tr>
<th>Slab Track System</th>
<th>Flexural Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleepers or Blocks Embedded in Concrete</td>
<td>Low</td>
</tr>
<tr>
<td>Sleepers on top of Asphalt-Concrete roadbed</td>
<td>High</td>
</tr>
<tr>
<td>Prefabricated Concrete Slabs</td>
<td>Low</td>
</tr>
<tr>
<td>Monolithic Designs</td>
<td>High</td>
</tr>
<tr>
<td>Embedded Rail</td>
<td>Low</td>
</tr>
<tr>
<td>Clamped and Continuously Supported Rail</td>
<td>High</td>
</tr>
</tbody>
</table>

As shown in table 3 each slab track system has different superstructure height which is decisive for its use. Systems with low overall height are very often used in tunnels where the free space is limited. A low height slab track system often results to lower tunnel construction costs. The Hydraulically Bonded Layer (HBL) preserves the same height in most of the slab track systems. The dimensions are in mm, ‘h’ is the height between the bottom of rail and the top of the
concrete/asphalt bearing layer, and ‘H’ (mm) is the height of the superstructure from the upper edge of the rail to the bottom of the hydraulically bonded layer (HBL).

Table 3: Comparison of overall heights of various slab track designs, all dimensions are in mm

<table>
<thead>
<tr>
<th>Name</th>
<th>CBL</th>
<th>ABL</th>
<th>HBL</th>
<th>h</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rheda Classic</td>
<td>360</td>
<td>-</td>
<td>300</td>
<td>99</td>
<td>931</td>
</tr>
<tr>
<td>Rheda-Berlin</td>
<td>447</td>
<td>-</td>
<td>300</td>
<td>32</td>
<td>951</td>
</tr>
<tr>
<td>Rheda 2000</td>
<td>240</td>
<td>-</td>
<td>300</td>
<td>61-81</td>
<td>773-793</td>
</tr>
<tr>
<td>Züblin</td>
<td>240</td>
<td>-</td>
<td>300</td>
<td>63</td>
<td>775</td>
</tr>
<tr>
<td>Heitkamp</td>
<td>557</td>
<td>-</td>
<td>300</td>
<td>32</td>
<td>1061</td>
</tr>
<tr>
<td>LVT</td>
<td>216</td>
<td>-</td>
<td>300</td>
<td>117</td>
<td>805</td>
</tr>
<tr>
<td>ATD</td>
<td>-</td>
<td>300</td>
<td>300</td>
<td>249</td>
<td>1021</td>
</tr>
<tr>
<td>BTD</td>
<td>200</td>
<td>-</td>
<td>300</td>
<td>270</td>
<td>942</td>
</tr>
<tr>
<td>walter</td>
<td>-</td>
<td>300</td>
<td>300</td>
<td>249</td>
<td>1021</td>
</tr>
<tr>
<td>sato</td>
<td>-</td>
<td>300</td>
<td>300</td>
<td>148</td>
<td>920</td>
</tr>
<tr>
<td>FFYS</td>
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<td>300</td>
<td>300</td>
<td>137</td>
<td>909</td>
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<td>Getrak</td>
<td>-</td>
<td>300</td>
<td>300</td>
<td>236</td>
<td>1008</td>
</tr>
<tr>
<td>Shinkansen</td>
<td>190</td>
<td>-</td>
<td>300</td>
<td>53</td>
<td>715</td>
</tr>
<tr>
<td>Bögl</td>
<td>200</td>
<td>-</td>
<td>300</td>
<td>80</td>
<td>752</td>
</tr>
<tr>
<td>ÖBB-Porr</td>
<td>240</td>
<td>-</td>
<td>300</td>
<td>80</td>
<td>792</td>
</tr>
<tr>
<td>FCC</td>
<td>273</td>
<td>-</td>
<td>300</td>
<td>32</td>
<td>777</td>
</tr>
<tr>
<td>hochtief</td>
<td>200</td>
<td>-</td>
<td>300</td>
<td>150</td>
<td>822</td>
</tr>
<tr>
<td>BES</td>
<td>257</td>
<td>-</td>
<td>300</td>
<td>32</td>
<td>761</td>
</tr>
<tr>
<td>BTE</td>
<td>200</td>
<td>-</td>
<td>320</td>
<td>69</td>
<td>761</td>
</tr>
<tr>
<td>inf undo</td>
<td>400</td>
<td>-</td>
<td>250</td>
<td>-</td>
<td>650</td>
</tr>
</tbody>
</table>

A study conducted in Deutsche Bahn’s network examined the alignment of different slab track designs as well as ballasted tracks. The ‘Q’ value depicted in figure 69 represents the quality of the track alignment incorporating the following parameters (Darr\textsuperscript{11}):

- Longitudinal elevation
- Transverse elevation
- Direction
- Buckling
Figure 69 is depicting different slab track systems and their performance after five years of measuring. The higher acceptable Q-value is 100. If this value is exceeded then the track must be re-aligned to comply with high speed railway standards. All slab track systems performed adequately without any need for maintenance. As it can be observed from the diagram, the Rheda system performed much better comparing to other systems. This diagram can influence the decision of slab track system to be constructed since the lower the Q-value, the lower and less frequent the maintenance need (Darr\textsuperscript{11}).

![Figure 69: Comparison of track-alignment quality of the various designs of slab tracks (Darr\textsuperscript{11})](image)

4.2 Technical and Economical Parameters

Other parameters that can influence the decision of the most appropriate ballastless design to be used are: the experience with the system, the speeds it can support, the overall height, the noise emissions, the need of maintenance, the construction costs, the speed of construction and the ease of renewal. All these parameters are summarized in table 4. The numbers used in the ‘assessment’ columns are the following: 1= advisable, 2=satisfactory, 3= needs improvement. The ‘cost’ column refer to manufacturing costs given from the upper edge of the HBL, tunnel sole or the substructure of the bridge. The ‘overall’ height column refers to the height from the upper edge of the HBL to the upper edge of the rail and the ‘daily performance’ column refers to an 8-hour shift length of track to be constructed.
Table 4: Technical and economic comparison of various slab track designs (Lichtberger22)

<table>
<thead>
<tr>
<th>type of design</th>
<th>year of construction</th>
<th>v (km/h)</th>
<th>overall height (cm)</th>
<th>Assessment noise</th>
<th>Q</th>
<th>assessment Q</th>
<th>cost €/m</th>
<th>daily performance (m)</th>
<th>assessment renewal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rheda</td>
<td>1972</td>
<td>300</td>
<td>63</td>
<td>2</td>
<td>15</td>
<td>1</td>
<td>1198</td>
<td>172</td>
<td>3</td>
</tr>
<tr>
<td>Rheda Berlin</td>
<td>1997</td>
<td>300</td>
<td>67</td>
<td>3</td>
<td>6</td>
<td>1</td>
<td>630</td>
<td>170</td>
<td>3</td>
</tr>
<tr>
<td>Züblin with sleepers</td>
<td>1988</td>
<td>300</td>
<td>60</td>
<td>2</td>
<td>30</td>
<td>3</td>
<td>550</td>
<td>200</td>
<td>2</td>
</tr>
<tr>
<td>Züblin BTE</td>
<td>1996</td>
<td>300</td>
<td>44</td>
<td>1</td>
<td>25</td>
<td>2</td>
<td>475</td>
<td>200</td>
<td>1</td>
</tr>
<tr>
<td>FTR</td>
<td>1988</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1750</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>ATD</td>
<td>1993</td>
<td>300</td>
<td>~70</td>
<td>2</td>
<td>25</td>
<td>2</td>
<td>600</td>
<td>200</td>
<td>2</td>
</tr>
<tr>
<td>BTD</td>
<td>1994</td>
<td>300</td>
<td>63</td>
<td>2</td>
<td>14</td>
<td>1</td>
<td>-</td>
<td>350</td>
<td>2</td>
</tr>
<tr>
<td>Getrac</td>
<td>1995</td>
<td>300</td>
<td>72</td>
<td>2</td>
<td>20</td>
<td>2</td>
<td>625</td>
<td>270</td>
<td>2</td>
</tr>
<tr>
<td>SATO, FFYS</td>
<td>1984</td>
<td>200</td>
<td>61</td>
<td>2</td>
<td>35</td>
<td>3</td>
<td>600</td>
<td>350</td>
<td>1</td>
</tr>
<tr>
<td>lawn track</td>
<td>1998</td>
<td>160</td>
<td>80</td>
<td>2</td>
<td>28</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Heitkamp</td>
<td>1998</td>
<td>160</td>
<td>78</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>-</td>
<td>200</td>
<td>3</td>
</tr>
<tr>
<td>FFC</td>
<td>1998</td>
<td>300</td>
<td>48</td>
<td>1</td>
<td>30</td>
<td>3</td>
<td>470</td>
<td>200</td>
<td>1</td>
</tr>
<tr>
<td>Infundo</td>
<td>1995</td>
<td>160</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>470</td>
<td>200</td>
<td>1</td>
</tr>
<tr>
<td>Saargummi</td>
<td>-</td>
<td>160</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

More information about economics and structural performance of slab track can be found in chapter 5.

4.3 Slab track use worldwide

The slab track systems have been extensively used around the world especially the last four decades. The pattern of slab track use seems to rise by the time due to the higher demands for high speed railways and heavy freight trains. Table 5 is illustrating the current lengths (km) of constructed ballastless systems worldwide according to the available bibliography. The most popular ballastless systems worldwide are the Bögl, Shinkansen, Rheda, Sonneville-LVT, Züblin, Stedef and Infundo-Edilon. Another important factor influencing the decision for the most suitable slab track design to be used is the experiences gained throughout the years of use and construction. The knowledge on slab track systems is limited and many statements about their performance are based in well examined hypothesis and not in actual proofs due to their relatively young status. So the older and lengthier (in terms of km construction) a system is the better information about its actual performance is available. This can be seen only as a positive feature.
<table>
<thead>
<tr>
<th>Slab Track Design</th>
<th>Country of design</th>
<th>Total construction (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bögl</td>
<td>Germany</td>
<td>4391</td>
</tr>
<tr>
<td>Shinkansen</td>
<td>Japan</td>
<td>3044</td>
</tr>
<tr>
<td>Rheda</td>
<td>Germany</td>
<td>2205</td>
</tr>
<tr>
<td>Sonnevile-LVT</td>
<td>Swiss</td>
<td>1031</td>
</tr>
<tr>
<td>Züblin</td>
<td>Germany</td>
<td>606</td>
</tr>
<tr>
<td>Stedef</td>
<td>France</td>
<td>334</td>
</tr>
<tr>
<td>Infundo-Edilon</td>
<td>Netherlands</td>
<td>211</td>
</tr>
<tr>
<td>ÖBB-Porr</td>
<td>Austria</td>
<td>122,2</td>
</tr>
<tr>
<td>IPA</td>
<td>Italy</td>
<td>100</td>
</tr>
<tr>
<td>PACT</td>
<td>UK</td>
<td>95,4</td>
</tr>
<tr>
<td>SATO</td>
<td>Germany</td>
<td>35,8</td>
</tr>
<tr>
<td>FFYS</td>
<td>Germany</td>
<td>33,1</td>
</tr>
<tr>
<td>BTD</td>
<td>Germany</td>
<td>32</td>
</tr>
<tr>
<td>ATD</td>
<td>Germany</td>
<td>31,7</td>
</tr>
<tr>
<td>Getrac</td>
<td>Germany</td>
<td>15,3</td>
</tr>
<tr>
<td>Walter</td>
<td>Germany</td>
<td>9,4</td>
</tr>
<tr>
<td>FFC</td>
<td>Germany</td>
<td>1</td>
</tr>
<tr>
<td>Heitkamp</td>
<td>Germany</td>
<td>0,39</td>
</tr>
<tr>
<td>BTE</td>
<td>Germany</td>
<td>0,39</td>
</tr>
<tr>
<td>BES</td>
<td>Germany</td>
<td>0,39</td>
</tr>
<tr>
<td>Lawn Track/Rasengleis</td>
<td>Germany</td>
<td>0,39</td>
</tr>
<tr>
<td>Hochtief</td>
<td>Austria</td>
<td>0,39</td>
</tr>
<tr>
<td>Deck Track</td>
<td>Netherlands</td>
<td>0,2</td>
</tr>
</tbody>
</table>

Figure 70 is showing the operating high speed lines as they appear today and the high speed lines as they are going to be in 2025 worldwide. A significant amount of these lines tends to be slab track ensuring high stability and minimum maintenance of the railway track.
Figure 70: High speed around the world in 2009 and forecast in 2025 (UIC International union of railways\textsuperscript{17})
5 Slab track versus ballasted track

The slab track can ensure very good geometrical stability of the track comparing to the ballasted track, on the other side it produces higher noise emissions. The extra protective measures need to be taken, increase the costs of the slab track construction significantly. In tunnels though, the slab track has been proved in many cases to be a more economical efficient solution due to its structure (lower height and no need for special preparation of the subsoil). Slab track is more beneficial in more favourable locations of the lines which can be adapted to the terrain and to existing structures by applying higher superelevation and superelevation deficiency values. One more advantage of the slab track is the easier and more economic vegetation control comparing to conventional track. In general the ballasted track is considered as a better solution in earth structures due to the lower costs of the construction (Lichteberger). On the other side, slab track maybe is more expensive to construct but the lower demand for track maintenance during the years and its high serviceability life time, suggest that in a long term perspective is economically more efficient.

Table 6: Components for ballast and slab tracks construction on earthworks (Nigel & Franz)

<table>
<thead>
<tr>
<th>Superstructure</th>
<th>Ballast Construction</th>
<th>Slab Tracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rails</td>
<td>Rail fastening</td>
<td>Rail fastening</td>
</tr>
<tr>
<td>Rail Support by Sleepers: Normal transverse beams</td>
<td>Rail Support: Discrete with sleepers or support points</td>
<td>Continuous support with embedded or clamped rails</td>
</tr>
<tr>
<td>Innovative solutions as frame or ladder</td>
<td></td>
<td>CSL or ASL</td>
</tr>
<tr>
<td>Ballast</td>
<td></td>
<td>HBL</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Substructure</th>
<th>Upper non-bonded supportive layer, possibly as frost protection layer (FPL)</th>
<th>Upper non-bonded supported layer: frost protection layer (FPL)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower non-bonded supportive layer: Earth works with compressed or improved embankment or cut formation</td>
<td>Lower non-bonded supportive layer: Earth works with compressed or improved embankment or cut formation</td>
</tr>
<tr>
<td></td>
<td>Foundation possibly compressed</td>
<td>Foundation possibly compressed</td>
</tr>
</tbody>
</table>
Table 6 is illustrating the differences of ballast and slab track construction superstructure and substructure. As it can be seen from the table the two systems share common and different features. The selection of the most appropriate track system to be used must be done considering the circumstances in which the installed track will be used in order to take approval from the Railway authorities (Nigel & Franz26).

5.1 Advantages of Slab Track

Generally speaking the advantages of the slab track design are the significantly reduced maintenance need in combination with its higher serviceability life, as well as its higher structural track stability. According to bibliography (Esveld5, Lichtberger22, Darr & Fiebig12, SSF36, Bastin31, Nigel & Franz26, UIC report15, Franz29) the reasons that may lead to the construction of a slab track system instead a ballasted one are the following:

- Lower maintenance need during its life cycle. No need for tamping, ballast cleaning and track lining results to a reduced cost approximately 20-30% for repairs comparing to that in ballasted track.
- Lower traffic hindrance costs.
- Higher life cycle, around 50-60 years compared to ballasted track (30-40 years) and possibility of almost full replacement at the end of the service life.
- More cost effective line positioning (as narrower curves at high superelevation and superelevation deficiency can be applied)
- No ballast or solid particles are whirled up on slab track.
- Higher safety against lateral forces and accommodation of higher axle loads.
- The eddy current brake can be applied without problems any time. (This is an advantage against ballasted track only in certain places such as signals or at station entrances. It cannot be seen as an advantage on plain line track.)
- Emergency vehicles and fire brigade vehicles can drive on the slab track in tunnels easily.
- Cost of vegetation control is either excluded or very reduced.
- Near maximum availability of the line and barely causes disturbances to the residents for maintenance during night shifts.
- Optimum design for high speed trains since it does not experience any problems such as drag forces at ballast.
- The slab track can compensate any excess in superelevation and in cant deficiency with freight trains or passenger trains without fears for dislocation of the track.
• Possible corrections up to 26 mm in vertical and up to 5 mm in horizontal position can be applied to counterbalance minor displacements.
• Reduced height and weight of the structure.
• The lack of suitable aggregates for a ballasted track in a certain area can also lead to a slab track design.
• Slab track maybe also more suitable in cases where the noise emissions and the vibration nuisance do not cause problems and are acceptable.
• In places where the release of dust from the ballast bed must be prevented for environmental reasons the slab track is a good solution.
• Excellent riding comfort at high speed (VOSSLOH43).
• Better load distribution, hence reduced dynamic load of subsoil (VOSSLOH43).
• Excellent load distribution, thereby reducing the pressure on unconfined soil layers and the subgrade (Miodrag24).
• Lower wear of vehicle running gear through good retention of track geometry (Nigel & Franz26).
• The higher braking forces enable for shorter braking distances (Franz29).
• Slab tracks allow for steeper route gradients (Franz29).
• The rail can be laid in lower temperatures since buckling is less of a concern comparing to ballasted track (Kucera, Bilow & Ball44).
• Lower construction costs in case track and rolling stock are adjusted to one another (Franz29).

5.2 Disadvantages of Slab Track

Slab track systems have various disadvantages too. In general the higher investment costs combined with the longer manufacture and installation time needed for its construction as well as the limited options in adjustments after construction and the higher air-borne vibration emissions, are few of the main reasons slab track is not the dominant track type used (Nigel & Franz26). The disadvantages of slab track are stated below according to the available bibliography (Esveld5, Franz29, Lichtberger22, UIC report15, fib42):

• The danger to have wrongly selected this design because of its lower maintenance cost due to the influence of the operational organization which is fully responsible for the railways maintenance after the construction. In many railways a part or the whole construction costs of a track are usually covered by governmental financial subsidies for sums invested in infrastructure. The total cost must be assessed and carefully examined in a fair way in order to select the most suitable track design.
• The deterioration of the track geometry in case the operational strength of the concrete slab track has been reached, can occur very suddenly and unforeseeably. Thus the operational strength of the slab track might be compared to the occurrence of rail fracture.

• Small adaptability to large displacements in the embankment. Large displacements in track can be compensated only by significant amounts of work.

• Slab track has an estimated life cycle of 50-60 years. Of course this is valid only if the presupposition that the expected acceptable settlements will occur. In case of a derailment or any other unforeseeable events which could cause greater damage than the expected one (damage in sensitive fastening elements) can result to long term and expensive track closures. Unfortunately due to the short age of slab track there is not enough information on the actual performance during its life time in order to assess and examine this issue with high validity.

• Slab track by its rigid structure it is ensured that its life time will be at least 50-60 years. The nature of the slab track does not allow for easy adjustments and repairs after its construction. That means that its quality during the construction must be checked and reassured carefully because any defect on its quality would either remain for the entire life cycle either high costly measures should be taken in order to eliminate it.

• Not many possibilities to apply any innovation or future updates after construction.

• Slab track cannot be built in soft clays, earthquake areas or embankments on soft peat layers.

• Ballastless track requires homogeneous sublayers which are capable to carry the imposed loads with minor or no settlements. This means that in many cases and especially in earth structures special attention should be given in the foundation preparations. The high costs which are associated with the above mentioned fact is the main reason for the limited use of the slab track.

• Higher noise emissions (5dB). To handle the increased noise, extra treatment is needed which result to higher construction costs.

• Very expensive repair concepts and long term closures due to the curing and hardening procedures of the concrete.

• The frost protective layer in earth structures must be applied in any case and it is much thicker comparing to the ballasted one. This is a prerequisite in order to reassure a lengthy life cycle.

• The cost of the reconstruction (after it has reached the end of its life cycle) of the slab track is not considered. One or two standardized types of slab track seem to be optimal solutions.

• Transitions between ballasted track and ballastless track require special attention.

• In many cases new mechanisms needed for production and repair.
5.3 Ballasted Track advantages & disadvantages

The ballasted track has relatively low construction costs comparing to ballastless track, it has high elasticity and high maintainability at relatively low cost. Another important advantage of the ballasted track is the high noise absorption (Esveld⁴). The 150 years experience with ballasted tracks makes the engineers more confident to deal with ballasted track problems and avoid the higher risk of dealing with problems concerning a relatively new design (Bezin⁴⁵). Many recent advances in ballasted track construction make them even more competitive against slab track. Few examples of these advances are the following (Bezin⁴⁵):

- Introduction of reinforced concrete or steel sleepers.
- Optimization of the rail geometry improves the wheel-rail contact condition offering a better load bearing capacity.
- Optimized rail pads and fastening providing better attenuation of the wheel-rail contact forces and of noise.
- Stone blowing and tamping machines provide more accurate corrections and faster maintenance.
- Better track resilience and resistance to settlements through the use of under sleeper mats as well as geogrids and geosynthetics between the different layers.
- The use of geotechnical retro-fitting techniques (e.g. lime cement columns), improving the bearing capacity of the subgrade, minimizing the possibility of settlements.

The final decision for the construction is taken considering both advantages and disadvantages of each system. The disadvantages which may lead the decision-makers to a slab track construction are the following (Esveld⁵):

- The ballasted track does not provide good lateral or longitudinal resistance with result to have “floating” track effects.
- Limited lateral resistance of the ballasted track, resulting to lower speeds in curves.
- The deterioration of the ballast creates particles which are damaging the rail and the wheels.
- The wear of the ballast plus the intrusion of the fine particles from the subgrade, contaminate the structure making it impermeable.
- Ballasted track is heavier and higher structure demanding stronger structures and larger foundations in case of viaducts and bridges.
- The track elements and the way they are put together during construction will highly influence the rate of the track deterioration.
- In bridges and tunnels where continuous ballast bed is the case, extra elasticity must be supplied by application of ballast mats, rail fastenings with increased elasticity. Nonetheless the usual maintenance must be provided at regular basis.
5.4 Slab Track costs

Certain feasibility studies have proved that the slab track is profitable only if the construction process will not cost 30% more than the construction cost for the ballasted track. The RHEDA design is the most used slab track design nowadays in Germany and it costs approximately 1.5 times more than the ballasted track design. Despite that it is widely used due to the long-term experience with this type (Lichtberger22). Taking into consideration the experience of the German network, the total costs in average is 20% to 40% more expensive than the cost of that of the ballasted track, and due to the almost zero need for maintenance it tends to be lower in the future (Giannakos21).

Few cost developments in the past showed that the estimated cost for maintenance after the construction was higher in a range of 100 years for tunnels and 40 years in earth structures. The prestige high speed line köln/Rhein-Main maintenance costs were found to be 30% more than the estimated ones before its construction. Attention has to be paid to the fact that the high original investment involves significant capital cost (Lichtberger22). The advantage of slab tracks to perform for longer time without significant amount of maintenance comparing to conventional ballasted track has long been understood. Results from recent evaluations in this subject propose that slab track is in a long-term perspective, more economically efficient as shown in figure 71 (Rudolf & Dirk32).

![Figure 71: Time depending value, ballasted track and slab track (Rudolf & Dirk32)](image)

The cheapest slab track per meter that can be found nowadays costs 500€, the average price for ballasted track per meter costs 350€. Most slab track designs nowadays cost 750 to 1100 €/meter
(superstructure costs). Although recent studies suggest that the price of the slab track decreases with the increasing of the constructed line, the price factor still remains 1.5-2 times more than the costs of a ballasted track (Lichtberger22).

The economic advantage of the slab track against the ballasted track increase only from the decreased need of maintenance required for unballasted track, e.g. the Rheda system used at the Bielefeld – Hamm route in Germany, which has withstood up to 200 km/h since 1972, is operating all these years almost maintenance free (Nigel & Franz26). On the other side the maintenance of ballasted track has been improving all the time. Ballastless track need maintenance too and in many cases can be proved very expensive depending on the damages nature. The possible repairs in a slab track will take much more time and money due to the non automated rehabilitation techniques. This has been proved at the high speed line Berlin-Hannover. A settlement defect (20mm) forced the trains to slow down at this point (70km/h). The repairs included lifting of the track and compactness in the area of 2-6 m depth. This works were carried out by special machinery during night shifts resulting to a very expensive remedy plan. If in the future the slab track found to be less reliable in terms of maintenance need, the economic efficiency pattern of the slab track against the ballasted track will be very poor (Lichtberger22).

The only clear case where slab track is economically efficient as against the ballasted track is in tunnels. This can be stated safely at least for tunnels where there is no need for extra treatment at the substructure (e.g. no need for ballast mats). In earth structures and in open areas, ballasted track is established to be the most economically efficient choice. In earth structures and open areas the price factor for slab track construction in many cases (long term settlements etc) is 2-2.5 higher than for ballasted track (Lichtberger22).

In a study conducted in 2007 (Steenbergen, Metrikine & Esveld23) it was shown that by increasing the width or/and by applying eccentric reinforcement in the concrete bearing layer (CBL), a significant amount of soil treatment can be avoided. The increased stiffness of the slab track in many cases can replace the need of massive soil improvements when slab track is applied in earth structures, making it economically competitive comparing to the ballasted track.

As reported by Bilow & Randich9 the construction cost of the Shinkansen system is 18% higher in cuts and 24% higher in fill sections than in ballasted tracks. The labour costs for maintenance are expected to be 30% lower than that required for ballasted track and the acceptable maximum settlement must be 30mm. The overall performance of this system is found to be satisfactory except for minor cracking due to alkali-silica reaction, cement asphalt mortar layers, and some warping of slabs in tunnels. The maintenance costs found to be 0.18 to 0.33 times that of ballasted track and the average total cost of the Shinkansen system 1.3 times more that of ballasted track, suggesting that the difference in construction costs will be balanced in 8 to 12 years.
In the U.S., the construction cost for class 4 ballasted tracks is approximately $970,000/mile and for class 9 ballastless track is about $1,240,000/mile. The annual cost for maintenance in ballasted tracks on heavy tonnage routes, including train delays and reroutes, is estimated to be $50,000/mile excluding the cost of tie replacement. The same cost for slab tracks is about $10,000/mile annually. Regarding to the above mentioned maintenance costs, it is evident that in a period of less than 8 years the slab track will recover the difference of the construction cost (Kucera, Bilow & Ball\cite{44}).

According to Profillidis\cite{26} the construction costs of the Rheda and Zublin system were 950 €/m and 800 €/m respectively (2006) comparing with the conventional ballasted track which costs of 510 €/m. Similarly the construction costs for slab track systems in France are almost twice that of ballasted track. The maintenance costs for slab track systems in Germany and Japan have been proved to be approximately 10% and 20 to 30% respectively of that required for ballasted track.

As stated by Miodrag\cite{24}, the slab track systems can be economically competitive comparing with ballasted track systems. The following table is illustrating this potential.

<table>
<thead>
<tr>
<th>Table 7: Summary of costs for the superstructure, excluding the concrete slab, for various systems in USD/yd (Miodrag\cite{24})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost estimate</td>
</tr>
<tr>
<td>--------------------------------</td>
</tr>
<tr>
<td>Conventional ballasted track</td>
</tr>
<tr>
<td>Wide Tie</td>
</tr>
<tr>
<td>Sinkansen</td>
</tr>
<tr>
<td>Edilon</td>
</tr>
<tr>
<td>Rheda</td>
</tr>
<tr>
<td>Balfour Beatty</td>
</tr>
<tr>
<td>Slab track ERS Integrated</td>
</tr>
</tbody>
</table>

In another study conducted by Zoeteman & Esveld\cite{47} a life cycle cost model (LCCA) for an embedded rail structure (ERS) was developed taking into account the labour costs, subgrade, traffic characteristics, traffic intensities, maintenance concepts, maintenance slots regime and risks. The study focused on the construction of the ERS railway track only comparing to the ballasted track. In figure 71 the results are clearly illustrated and the results show a 40% higher construction costs for the ERS and 20% less total discounted life cycle costs comparing to the ballasted tracks used in Netherlands.
One very important life cycle cost study published in 2008 by Kondapalli & Billow for PCA (Portland Cement Association) is summarizing the economic benefits of the slab track as compared to ballasted track when used in heavy freight traffic and combined freight and high speed rail service. Three prototypes were analysed as shown in table 8 and slab track prove to offer 7% to 11% total savings comparing to ballasted track.

Table 8: Present value of costs in Dollars per mile for three prototypes (Kondapalli & Billow)

<table>
<thead>
<tr>
<th>Cost category</th>
<th>A. Heavy high volume freight</th>
<th>B. Heavy moderate volume freight + 125 MPH passenger</th>
<th>C. Moderate freight + 200 MPH high speed passenger</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ballasted track</td>
<td>Slab track</td>
<td>Ballasted track</td>
</tr>
<tr>
<td>Track construction</td>
<td>1,166,000</td>
<td>1,292,000</td>
<td>1,166,000</td>
</tr>
<tr>
<td>Track maintenance</td>
<td>8,057,000</td>
<td>6,926,000</td>
<td>4,551,000</td>
</tr>
<tr>
<td>Operating cost</td>
<td>13,836,000</td>
<td>13,269,000</td>
<td>6,968,000</td>
</tr>
<tr>
<td>Derailment cost</td>
<td>137,000</td>
<td>7,000</td>
<td>69,000</td>
</tr>
<tr>
<td>Total present value</td>
<td>23,196,000</td>
<td>21,494,000</td>
<td>12,755,000</td>
</tr>
<tr>
<td>Net benefit of slab track</td>
<td>$1,702,000</td>
<td>7% Savings</td>
<td>$970,000</td>
</tr>
</tbody>
</table>

In a LCC analysis conducted by Esveld the construction as well as the annual costs of three slab track (1.Rheda structure, 2.ERS not integrated into the concrete sub-structure, 3.ERS integrated into the concrete substructure) and two ballasted designs (1.conventional ballasted track, 2.Ballasted track with high-speed specifications) are found and compared. The cost estimations
include only the cost of the superstructure on top of the concrete sub-structure. The results are summarized in figure 73 and table 9 below.

![Figure 73: Annual costs in EUR/m based on NPV analysis (Esveld)](image)

Table 9: Construction and annual costs (EUR/m) for four different slab track design configurations and one ballasted track with high speed specifications (Esveld)

<table>
<thead>
<tr>
<th>Present cost estimate:</th>
<th>Construction</th>
<th>Annual Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab track, ERS, NI (Not integrated)</td>
<td>EUR 1,200</td>
<td>EUR 90</td>
</tr>
<tr>
<td>Slab track, ERS, NI, optimized</td>
<td>EUR 860</td>
<td>EUR 70</td>
</tr>
<tr>
<td>Slab track, ERS, INT (Integrated)</td>
<td>EUR 910</td>
<td>EUR 80</td>
</tr>
<tr>
<td>Rheda</td>
<td>EUR 1,270</td>
<td>EUR 100</td>
</tr>
<tr>
<td>Ballasted track</td>
<td>EUR 1,000</td>
<td>EUR 110</td>
</tr>
</tbody>
</table>

Despite several effects such as, higher availability of the track, lower dead weight on engineering structures, reduced structure height and savings on noise-reducing measures, were not taken into consideration, the LCC analysis clearly illustrates the advantages of the slab track designs.

According to Darr\textsuperscript{11} the slab track designs that have been used in Deutsche Bahn’s network so far, function very satisfactorily by maintaining their track-bed stability even under high-speeds and heavy traffic loads. On the other side, the ballasted tracks needed maintenance work very frequently in order to keep the track aligned properly regarding the standards for high-speed lines. These maintenance works result to high costs and reduce the availability of the lines. The diagram shown in figure 73 confirms Darr’s\textsuperscript{11} statement about track stability of slab track against ballasted track. The value ‘Q’ is a quality coefficient which has arrived from geometrical records taken by a self-propelled track measuring vehicle, working over ballasted and slab track sections in Deutsche Bahn’s network for five years. ‘Q’ value incorporates the following parameters: transverse elevation, longitudinal elevation, direction and buckling. The lower the ‘Q’ value the
better the track-bed alignment. The maximum acceptable limit of ‘Q’ is 100, and it has been exceeded from various ballasted tracks even though they were thoroughly maintained in the meantime to correct track alignment (see right side of the diagram). As it can be observed in figure 74 the slab track systems kept a very high quality of track alignment with no need for maintenance. The results of this study indubitably indicate that slab tracks perform much better under high-speeds staying maintenance free, providing a more cost effective solution in a long term perspective.

Figure 74: Alignment of slab track and adjacent sections of ballasted track (Darr11)
6 Slab Track Modeling

The aim of this chapter is to develop a 3-D model of a slab track using ABAQUS FEA software in order to perform an analysis under static loading. The results are compared with the results obtained from a similar 3-D modelling of a ballasted track (Feng14). This comparison clarifies the different structural behaviours of ballasted and ballastless tracks. The simulated slab track system has high flexural stiffness and it belongs to the discrete rail support category with encased sleepers in the concrete bearing layer (similar to Rheda).

6.2 ABAQUS Modules

The different modules that are used for the slab track modelling are the following:

- Parts module is used to create different separated parts.
- Property module to assign different properties to the different parts.
- Assembly module to assemble the model by combining the different parts.
- Step module to create the required simulation steps.
- Interaction module to allow different parts to interact together.
- Loads module to create loads, set the boundary conditions and the predefined fields.
- Mesh module to mesh the model according to the element type used as well as the geometry of the model.

6.3 Elements

A model can be designed in 3D space, 2D planar space and axisymmetric space. There are many different kind of elements that can be used to build a model in ABAQUS. Those are:

- Beam element
- Solid element
- Rigid element
- Spring and Dashpot element

For this 3D slab track model, beam elements (Euler-Bernoulli) were used for the rail, solid elements for the sleepers and the track-bed, and spring elements for the rail-sleeper connections.
6.4 Type of analysis performed

The 3D slab track model has been built to study the global response of the railway track system under static loading simulating the loading of a train. Hence a general static analysis is performed to derive deflection and stress values indicating the overall performance of the track in order to compare it with the performance of a ballasted track under the same loading conducted by Feng14.

6.5 Model Description

The analysed 3D model is similar to the German slab track Rheda 2000. All dimensions and properties used for the model are identical to the real life Rheda 2000 design system. This system has high flexural stiffness and is one of the most used slab track designs around the world. The main reason the author decided to simulate this ballastless system is the detailed information that can be found in bibliography about its properties, dimensions and design procedures.

6.5.1 Model’s Geometry

The geometry of the model is clearly illustrated in the following figures. The cross section detailed dimensions are shown in figure 75 and 76 and are identical to a typical Rheda 2000 design. The rail used is UIC60 and it’s the standard selection for high speed railways (see figure 77). In figure 78 the actual model is depicted together with some basic dimensions for each layer of the track. The figure 79 is showing the whole 42.9 m long 3D slab track model designed in ABAQUS.
Figure 75: Dimensions of the slab track model in mm (cross-section) (Rail One^{30})

Figure 76: Track top-view dimensions and sleeper of the 3D model

Figure 77: Cross-section of UIC 60 rail
6.5.2 Properties

The properties for all the structural components needed to build the model are clearly shown in table 10.
Table 10: Properties of the slab track model components

<table>
<thead>
<tr>
<th>Track Components</th>
<th>Unit weight, $\gamma$ (kg/m³)</th>
<th>Modulus of elasticity, $E$ (Gpa)</th>
<th>Poisson's ratio, $v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rail</td>
<td>7850</td>
<td>207</td>
<td>0.28</td>
</tr>
<tr>
<td>Sleeper</td>
<td>2400</td>
<td>70</td>
<td>0.2</td>
</tr>
<tr>
<td>CBL</td>
<td>2400</td>
<td>34</td>
<td>0.2</td>
</tr>
<tr>
<td>HBL</td>
<td>2400</td>
<td>5</td>
<td>0.2</td>
</tr>
<tr>
<td>FPL</td>
<td>2400</td>
<td>0.12</td>
<td>0.2</td>
</tr>
<tr>
<td>Subsoil</td>
<td>2000</td>
<td>0.01</td>
<td>0.4</td>
</tr>
</tbody>
</table>

6.5.3 Loads

To study the effect of standard train loading for high speed railways a 42.9 m long slab track is modelled. As shown in figure 80 the technical specifications for interoperability relating to rolling stock $O_{BA}=2.6m$ and $O_{BS}=4.9m$ were taken respectively according to the UIC code. In figure 81 the load formation used in the 3D slab track model is indicated. The loads were applied in a static linear step from 0 to 100% to find equilibrium. The actual designed ABAQUS model under the UIC standard loading is shown in figure 81.
6.6 Comparison of Ballasted and Slab track models

In this chapter the displacement and stress diagrams of the slab track model are illustrated in figure 82 and 84 respectively. The same diagrams are depicted in figures 83 and 85 for an identical 3D ballasted model taken from a study conducted by Feng\textsuperscript{14}. The magnitude of displacement for both models showing the deformation pattern of the railway track is illustrated in figure 85 and 86. The values of displacements and stresses for both models were taken 0.54 and 3m respectively under the top surface of the concrete bearing layer (CBL) and along the centre line of the track bed.
Figure 82: *Slab track displacements along the path*

Figure 83: *Ballasted track displacements along the path*
Figure 84: Slab track stresses along the path

Figure 85: Ballasted track stresses along the path
The results indicate that the slab track model deflects considerably less than the ballasted model under the same loading conditions. The stress values obtained from the previous mentioned depth (3m from the top of the CBL) for the slab track model are considerably lower than those obtained from the ballasted track due to the significantly higher flexural stiffness of the Slab.
track. The stress results were taken 3m below the top layer to find out what is the influence of the forces in the subsoil which is the softer part of the structure. The slab track model exerts considerably less stresses suggesting that the whole structure will maintain its geometry for much longer time. The displacement results were taken at the bottom of the hydraulically bonded layer or the top of the frost protection layer. It is obvious that the HBL and the CBL can resist deformations more effectively comparing to the ballasted track due to their higher structural stiffness.

Observing the figures 86 and 87 someone can realise how differently the two track beds behave under loading. The slab track deformation is smoother by distributing the loads in much larger areas. On the other side the ballasted track deformation is sharper near the points where the load is located and almost undeformed at the areas far from the loads. This is due to the significantly lower stiffness of the ballasted track bed which is unable to distribute the forces in large areas.
All the different slab track systems available are introduced in this thesis. The systems are categorized according to their construction principles and a detail description of each system is given. Information and detailed description on structural behavior, design dimensions, country of origin, further developments, and in many cases description of the construction method, of the slab track system give a better understanding in this subject. Knowing the peculiarities of each slab track system, it is easier to decide which is the most suitable to use in a specific railway project.

The structure of ballastless tracks and the properties of each layer are analytically described in this thesis. The application of slab track has certain limitations resulting to special requirements: for the subsoil, in transition points, for noise emissions and vibrations, for signaling and electro-technical installations, when applied in tunnels and bridges. Many different ways to meet these requirements for each case are explained. Knowledge of how to deal with these requirements is crucial to ensure a successful slab track construction and future smooth running operations.

The differences between slab track systems and ballasted tracks as well as their advantages and disadvantages have been discussed. It is known that the ballasted track is the dominant structure used today, though the advantages of slab track comparing to ballasted track especially for high speed lines and freight lines are significant. It has been shown in the thesis that each slab track has its own characteristics in every aspect. The demand for slab track use is rising, and these must be clearly recognised in order to make future improvements and select the most suitable slab track according to the needs of each project.

The construction costs of ballastless systems maybe higher, but the reduced need for maintenance combined with the high structural stability and their longer lifespan as well as the higher demands of the new high speed lines suggest that in many cases the use of slab track construction is more feasible. To select the appropriate track system to be used, the definition of specific evaluation criteria which can reliably test its efficiency is crucial. References have been given for possible criteria to be considered in order to indicate the best solution. The LCC studies done by different researchers also show that slab track has net benefit of 7-11% compared to ballasted track. It is recommended that LCC and LCCA should be included in the decision process of track form selection.

Finally, a 3D slab track model was created to check the global response of the railway track due to passing train load. The results were compared with an identical 3D ballasted model. As expected, a slab track model with high flexural stiffness similar to Rheda 2000 deforms considerably less than a ballasted track. The ballasted track is unable to distribute the forces in large areas resulting to extensive deformations and high stresses around the loading areas. The results suggest that the need of maintenance and the life cycle of a slab track would be
considerably less and considerably higher (at least double), respectively. The outcome of the study is valid in favourable conditions for both models showing their principal behaviour under static loading.

To conclude, the author would like to urge the need for further studies in slab track performance in terms of structural stability, maintenance need and overall cost analysis in order to better understand the limitations of the slab track concept. Updates of the most successful slab track designs must be implemented as the knowledge about their performance increases. Most slab track systems that are of significant age (~40 years) in many cases have been proved better than ballasted tracks, others not. This depends mainly in the geological conditions under the slab track superstructure (weak soil, stiff stable soil, tunnels etc). It is important to have in mind that the slab tracks designed in 1970’s nowadays have been considerably improved. Hence the derived results and conclusions from older designs may be able to indicate successfully the principal behaviour of slab tracks but on the other side they could be proved less representative for the new or updated designs. The slab track designs gain more and more popularity in railway projects as the railway speed increases. There are many newly updated designs constructed recently around the world and much more to be built in the near future. This fact alone show that in the following years the knowledge about the slab track systems will increase rapidly allowing for much more accurate comparisons with the ballasted systems. Slab tracks may be proved to be the dominant design in the future high-speed railways.
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