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Thesis of Master Degree

COMPARISON OF BALLASTED AND SLAB TRACK BASED ON LCC ANALYSIS

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Canım Ailem,

Bugüne kadar desteğinizi benden hiç esirgemediğiniz ve bana hep güvendiğiniz için size sonsuz teşekkür ederim. Attığım her adımda sizleri de düşündüğümü bilmenizi isterim.

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Abstract

Since the birth of modern railways, the desire for faster journeys has led to the emergence of the slab track railway system. Although the speed played a major role in the development of slab track, increased axle loads, and environmental concerns have also made slab track more popular today.

In this thesis, ballasted track and slab track systems are examined separately in terms of technical and economic aspects together with environmental impacts. Then, the two systems are compared and the advantages and disadvantages of each are discussed.

Finally, the "Life Cycle Cost Analysis" is developed for both systems to analyze their efficiency during their service lives. Results show that, slab track is not an attractive solution only at high speeds but also for high tonnages.

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1. INTRODUCTION

1.1. Study Motivation

The aim of this study is to analyze the ballasted track and slab track concepts and compare them in terms of technical and economic aspects. This comparison is fundamental to understand under which condition the slab track is more beneficial. A simplified Life Cycle Cost Analysis is introduced to give a better idea about the economic advantage of the slab track in the long term. The results of the study should not be inferred that one system is better than the other in all conditions. Nevertheless, it can be used as a basis for more comprehensive studies.

1.2. History of Railway

The first examples of railway are quite far from today's modern concept. In ancient times, it began as a roadway intentionally arranged with grooves to provide a designated route for wheels. But it is hard to distinguish whether those cuts were made on purpose or simply worn out by traffic. Well-known examples are to be found in the streets of Pompeii [1].

The first is the famous Diolkos or railed way near Corinth in Ancient Greece which was used to transport boats across the Isthmus of Corinth. Instead of circumnavigating around the Peloponnese peninsula, the ancient Corinthian ships were quickly transported across the Isthmus. It is considered as the predecessor to the modern railway. Transportation across the Isthmus continued from approximately 600 B.C. to AD 150 [2]

Picture 1 - Remains from the Diolkos [2]

The first rail guided tracks were introduced in the 16^{th} century. Back then, wooden roadways were used to create low frictional surface for the mining vehicles in England. During the economic crisis in 1760's, iron was overproduced, and the sector was in search of a different usage area for it. A brilliant idea came up to cover wooden rails with iron plates to reduce running resistance [3].

The first full-scale working railway was built in the United Kingdom in 1804 by the British Engineer Richard Trevithick after the invention of the steam engine [4]. In 1825 the first railway for passengers was opened between Stockton and Darlington. On the mainland of Europe, Belgium was the first country to open a railway (Mechelen - Brussels). Belgium was quick to create a connection with the German hinterland bypassing the Dutch waterways. The first railway In the Netherlands (Amsterdam - Haarlem) came into existence much later: only in 1839. Here the railway was regarded as a big rival of the inland waterways [3, p. 1].

Railways reduced the costs of shipping and allowed for fewer lost goods, compared with other transport means. The demand on railways created a competition between the private service providers and this encouraged technological developments. As a result, load capacity and speed increased drastically, and the railway became a monopoly in the sector until the twentieth century [3], [5]. Figure 1 shows how fast the axle load and speed increased over time.

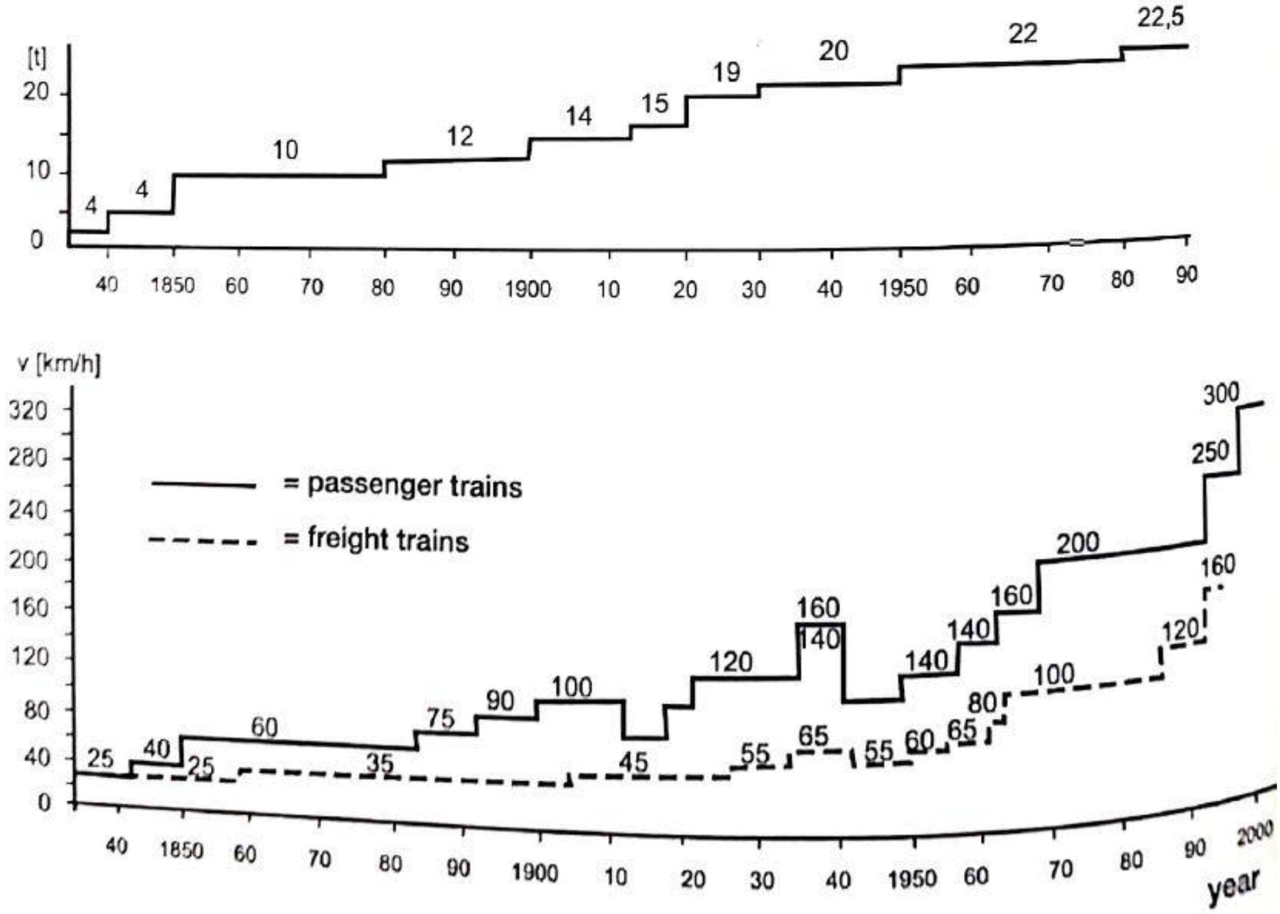

Figure 1 - Chronological development of axle loads and train speeds [5]

2. TYPES OF TRACKS

There are many different railway track systems that exist around the world. In this section, the most known track types are classified in 4 clusters. Brief information is given for each type. Afterwards, more comprehensive information is furnished about ballasted track and slab track to provide a basis for comparison of those two types.

2.1. Ballasted Track

Today, predominantly almost all existing railways are of the ballasted track type. This kind of track system consists of sleepers and rails placed on a layer of granular material known as ballast. Figure 2 shows the construction principle of the conventional track structure.

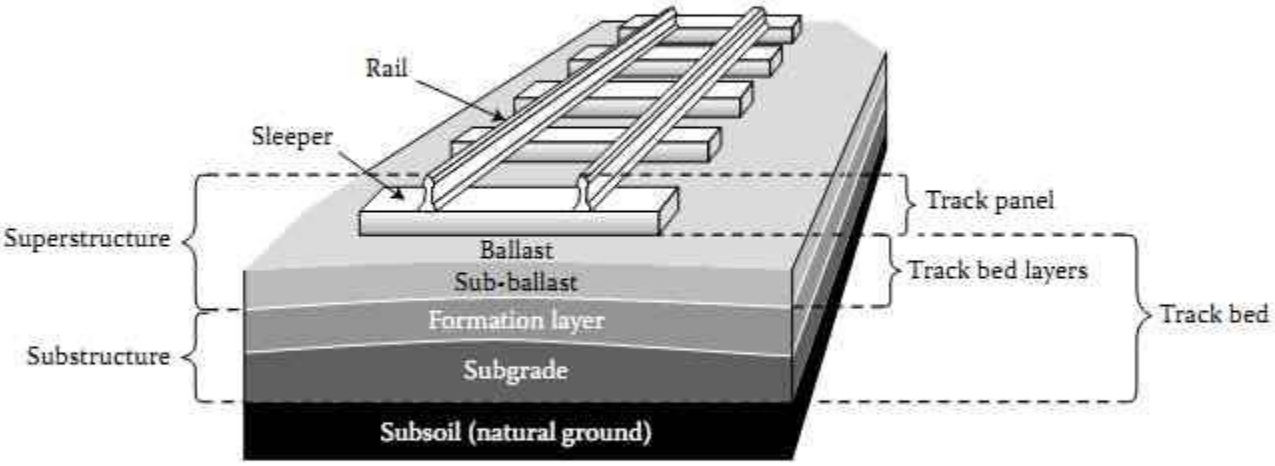

Figure 2 - Cross-section of ballasted track [1]

According to Esveld C., since the beginning of the railways, the principle of the ballasted track structure has not changed substantially. Important developments after the Second World War include the introduction of continuous welded rail, use of concrete sleepers, heavier rail-profiles, innovative elastic fastenings, mechanization of maintenance and introduction of advanced measuring equipment and maintenance management systems. As a result, the traditional ballasted superstructure can still satisfy high demands, as demonstrated by the TGV-tracks In France [3, p. 203].

The early life stage of railway engineering, the function of the ballast was not fully understood in terms of bearing capacity. In the beginning, wheeled transport was hauled by horses. By the time heavy locomotives came on the scene, it turned out that the layer beneath the sleepers should be deep enough to distribute the load to the ground and to ensure the track stabilization. Today, the required depth of the ballast varies depending on speed, axle load and gross annual tonnage. But in general, it should never be less than 150mm [6].

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[1] Picture source: http://www.khurramhashmi.org/crbasic_info/rts_1.html

In the ballasted track, the rails lay on sleepers. There are various types of sleepers used in railways, according to their convenience, availability, economy, and design. Today, timber and concrete sleepers and steel sleeper - to a limited extent- are used [3].

The sleepers need to provide the following basic functions [6]:

- Spread wheel loads to ballast
- Hold rails to gauge and inclination
- Transmit lateral and longitudinal forces
- Insulate rails electrically
- Provide a base for rail seats and fastenings

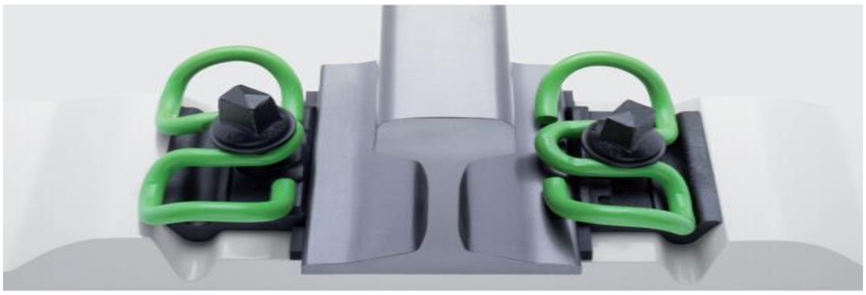
Picture 2 – From the left to the right: Wooden, steel, concrete sleepers

Sleepers and rails are connected to each other by fastening systems. The system guarantees a resilient connection between rail and sleeper to overcome all forces arisen by traffic loads and temperature variations [6].

The general functions and requirements of fastening systems are: [3, p. 219]:

- To absorb the rail forces elastically and transfer them to the sleeper;
- To damp vibration and impacts caused by traffic as much as possible;
- To retain the track gauge and rail inclination within certain tolerances;
- To provide an electrical insulation between the rails and sleepers, especially in case of concrete and steel sleepers.

The fastenings can be divided into two distinctive types; rigid and elastic. The introduction of continuous welded rail track gave rise to the need for fastenings with greater elasticity [3]. Therefore, the elastic systems are more widely used in today’s applications. There are a lot of different types of fastening systems depending on properties and the structure of sleepers, but one set of the system is commonly composed by 4 screw spikes, 4 screw dowels, 4 tension clamps, 4 guide plates, 2 rail pads.



Picture 3 - Vossloh W14 Rail Fastening System

2.2. Slab Track

Although most of the current railway tracks are still of a traditional ballasted type, recent applications tend more and more towards non-ballasted track [3]. In case of slab track, the ballast material is replaced by a concrete slab that provides support for the track. Usually the sleepers are integrated in the concrete slab as well. The rails are mounted with a similar type of fasteners like the ones used for ballasted track.

Picture 4 - FF Bögl Slab Track System

Increase in speed has been the main factor for the development of the slab track. If train speed increases to a certain level, the track structure and the supporting ground experience extreme dynamic motions. These motions cause rapid deterioration of the track, ballast and sub ballast, including possible derailment and ground failure [7]. Slab track systems, recognized as safer and more convenient, are currently in use for high-speed trains in many countries. But speed is not the only factor that makes slab track more attractive. In the past projects were mainly assessed based on investment cost and these studies showed that slab tracks are quite expensive compared to ballasted tracks. In fact, taking life cycle costs into consideration, slab track systems might offer more competitive costs even for low speeds.

2.3. Embedded Track

These tracks are embedded in the road and are used by trams and light rail and for level crossings. The unique feature about this kind of track is that it can share the road with other types of traffic, like cars and buses. The track itself can be either ballasted or slab track. In the case of the embedded track, an elastic material replaces the fasteners. This elastic compound surrounds almost the entire rail profile except for the rail head.

2.4. Magnetic Levitated Trains

Magnetic Levitated (MagLev) trains are based on a completely different principle. As the train is carried by magnets, instead of wheels, the track act merely as a guideway, hosting the magnets required for train levitation.

3. DETAILS OF BALLASTED AND SLAB TRACKS

3.1. Ballasted Track

As mentioned in the previous chapter, in this system sleepers and rails are laid down on a layer of granular material called ballast. Since the fastening systems and rail types are the same or quite similar in both ballasted track and slab track systems, the focus of attention in this chapter will be the specification of ballast layer and its sublayers.

3.1.1.Track Structure and Requirements

The conventional railway track consists of a flat frame made up of ballast-supported rails and sleepers. The ballast bed lies on a sub-ballast layer that creates the transition layer to the formation.

Ballasted track structure consists of (top-down):
- track superstructure:

- rails,
- fastening of the rails to the rail support,
- rail support (sleepers),
- Ballast,
- Sub-ballast,

- track substructure:

- Formation Layer (Sand Blanket),
- Subgrade,
- Subsoil.

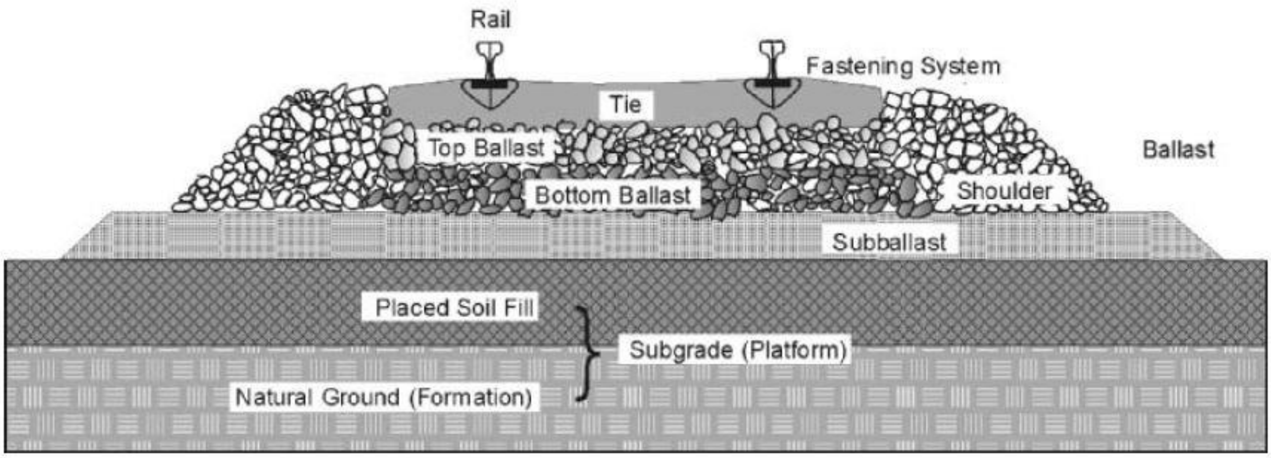


Figure 3 – Cross section of Ballasted Track [8]

3.1.1.1. Subsoil

Conventionally, rail tracks are based on compact ballast platforms placed on natural subsoil. This layer is the last link in the structure of track formation. If the bearing capacity is not sufficient, dynamic loads will result in plastic deformation of the subsoil over time [5].

The reasons that may affect the subsoil quality are [5]:

- High dynamic and static loads on the subsoil
- Inadequate compaction of the soil
- Weak drainage
- High ground water
- Wide sleeper spacing
- Heavy or small support surface sleepers

The damaged subsoil formation increases maintenance and rehabilitation work frequency, causes speed restriction and shortens the service life. The irregular settlement of the track creates overstress on sleepers and rails.

The proper soil has to have the following properties [5]:

- High bearing capacity, able to carry static and dynamic loads with only minor settlements
- Elasticity
- Endurance to erosion
- High water permeability
- Volume and filter stability
- Resistance to freeze-thaw cycle
- Economic self-sufficiency in supply and construction

The peak static load on soil formation must not exceed the threshold of 0.1 MN/m^2. This value is 0.3 MN/m^2 for ballast pressure. The consequential rise in dynamic stress is important for all soil types at greater train speeds. The compressive strain below a ballasted track can achieve values of up to 100 kN/m^2 when the speed increases from 100 to 300 km/h. Under severe conditions, compressive strains may increase up to 50%. Using slab track reduces the compressive strains lower than 5 kN/m^2 below the supporting material [5].

3.1.1.2. Subgrade

The subgrade is the first layer on natural soil. It creates a suitable platform on which the track structure can be built. Stress arising due to the traffic running on the rail can reach up the 5 meters below the bottom of the sleepers. This is far beyond the ballast and sub-ballast depth. Therefore, the subgrade is an important component that supports the resiliency of the superstructure [8].

Common features of the subgrade are listed below, and the various types of problems are shown in Table 1 [8]:

- Provide a stable platform to construct the track on.
- Limit progressive settlement caused by repeated traffic loading.
- Limit consolidation settlement.
- Prevent massive slope failure.
- Restrict swelling or shrinking caused by water content change.

Type	Causes	Features
Progressive shear failure	-Repeated over stressing subgrade -Fine-grained soils -High water content	-Squeezing of subgrade into ballast shoulder -Heaves in crib and/or shoulder -Depression under sleepers trapping water
Excessive plastic deformation (ballast pocket)	-Repeated loading of subgrade -Soft or loose soils	-Differential subgrade settlement -Ballast pockets
Subgrade attrition with mud pumping	-Repeated loading of subgrade stiff hard soil -Water presence -Contact between ballast and subgrade -Clay-rich rocks or soils	-Muddy ballast -Inadequate subballast
Softening subgrade surface under sub-ballast	-Dispersive clay -Water accumulation at soil surface -Repeated train loading	- Reduces sliding resistance of subgrade soil surface
Liquefaction	-Repeated dynamic loading -Saturated silt and fine sand -Loose state	-Large track settlement -More severe with vibration -Can happen in subballast
Massive shear failure (slope stability)	-Weight of train, track, and subgrade -Inadequate soil strength	-Steep embankment and cut slope -Often triggered by increase in water content
Consolidation settlement	-Embankment weight -Saturated fine-grained soils	-Increased static soil stress as from weight of newly constructed embankment -Fill settles over time
Frost action (heave and softening)	-Periodic freezing temperature -Free water -Frost-susceptible soils	-Occurs in winter/spring period -Heave from ice lens formation -Weakens from excess water content on thawing -Rough track surface
Swelling/ shrinkage	-Highly plastic or expansive soils -Changing moisture content	-Rough track surface -Soil expands as water content increases -Soil changes as water content decreases
Slope erosion	-Surface and subsurface water movement -Wind	-Soil washed or blown away -Flow onto track fouls ballast -Flows away from track can undermine track
Slope collapse	-Water inundation of very loose soil deposits	-Ground settlement
Sliding of side hill fills	-Fills placed across hillsides -Inadequate sliding resistance -Water seeping out of hill or down slope is major factor	-Transverse movement of track

Table 1 - Major subgrade problems and features

3.1.1.3. Formation Layer (Blanket)

The blanket is a layer over the full width of formation between subgrade and ballast that specifies coarse-grained with designed thickness. It is essential to provide a layer under the ballast bed with adequate strength to run safe operations of heavy axle loads.

Main roles of formation layer are [9]:

- To distribute the load better on the subgrade by modifying the stiffness

- To prevent ballast penetration into the subgrade
- To reduce the stress on the subgrade
- To disallow the passage of fine particles that may cause fouling of ballast
- To prevent mud pumping
- To drain the water from the subgrade
- Protect the subgrade from erosion and climatic changes

Formation layer should cover up the entire width of the formation from shoulder to shoulder. The layer is formed by well graded coarse-grained material, and the size of the material should be between the curves that are shown below in Figure 4. Plastic fines contenting finer material than 75μ cannot exceed 5% of the whole material. Percentage can reach up to 12% if the fines are non-plastic. The Uniformity coefficient (Cu) should be greater than or equal to 4, more than 7 is preferable. The coefficient of curvature (Cc) should be within 1 and 3 and no skip grading is allowed [10].

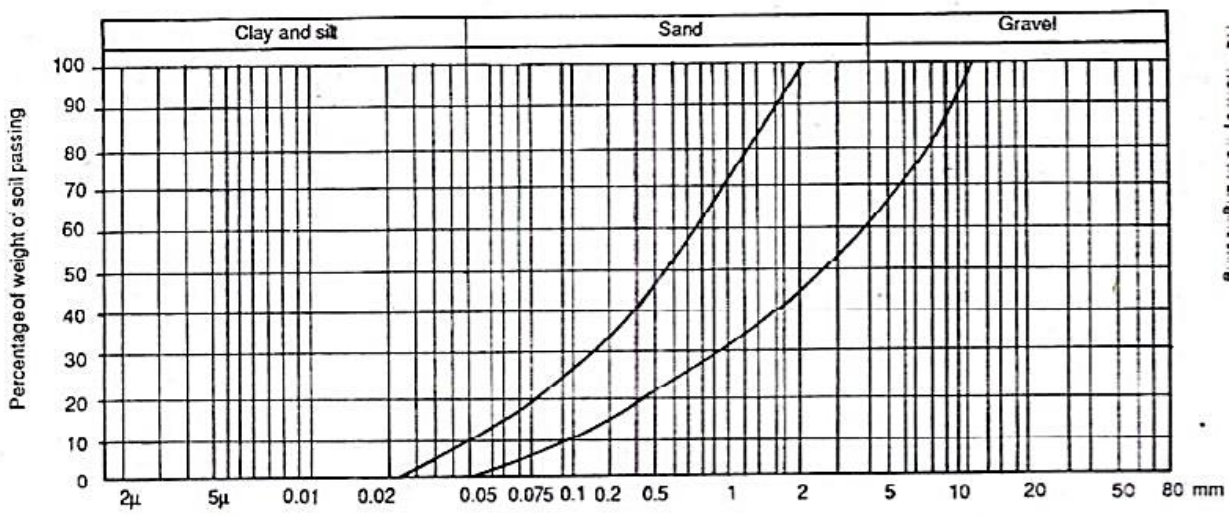


Figure 4 - Enveloping curves for blanket material [11]

3.1.1.4. Sub-ballast

The sub-ballast is a layer that gives a solid support for the ballast and reduces the leakage of water onto the underlying ground. Sometimes an elastic mat is placed on the sub-ballast layer to reduce vibration.

Main functions of the sub-ballast are listed below [8]:

- Maintain separation between the ballast and subgrade particles.
- Prevent attrition of the hard subgrade surface by the ballast.
- Reduce pressure from the ballast to values that can be sustained by the subgrade without adverse effects.
- Intercept water from the ballast and direct it to the track drainage system.
- Provide drainage of water flowing upward from the subgrade.
- Provide some insulation to the subgrade in order to prevent freezing.
- Provide some resiliency to the track.

Appropriate materials for sub-ballast are frequently found in nature. The aggregate must be resilient to the deterioration of freezing/thawing and repeated train loading cycles. But it is not required that material should be as durable as ballast because it has smaller dimensions and exposes lower stresses. Subballast must be drained properly. In this way, it is not saturated during repeated train loading. Saturated and undrained sub ballast materials can substantially deform and even liquefy during train loading [8].

To fulfill the main functions, the sub-ballast gradation must meet the requirement in Figure 5:

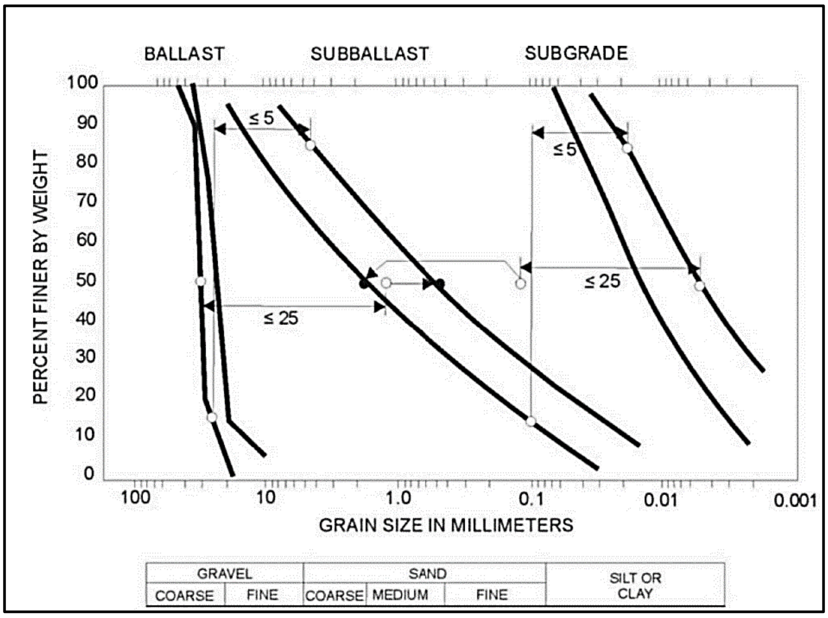


Figure 5 – Sub-ballast satisfying filter criteria

3.1.1.5. Ballast

Track ballast creates a track bed on which sleepers are laid. It is packed between, below and around the sleepers. It is used to distribute the load off the sleepers, to facilitate drainage of water, and to keep down vegetation that might interfere with the track structure [12].

Figure 3 shows the ballast component of the track divided into four zones [8]:

- Crib—material between the sleepers
- Shoulder—the material beyond the sleepers ends, down to the bottom of the ballast layer
- Top ballast—the upper portion of supporting ballast layer that is disturbed by tamping
- Bottom ballast— the lower portion of supporting ballast layer, which is not disturbed by tamping and generally is more fouled

The ballast bed can possess significant bearing strength in the vertical direction as a result of internal friction between the grains. But its capacity is very low against tensile stresses. Beside its bearing capacity, it also performs an important role as drainage during downpours - an aspect which should not be underestimated. Before installing the ballast layer, platform must be flat and settlement differences must be limited to 10mm [3] [8].

Good quality track ballast is made from crushed stones, gravel or crushed gravel with grading 25/60 mm for the main lines and 15/40 mm for the secondary tracks, switches and level crossings. To obtain the finest interlocking characteristics and resistance to the longitudinal and lateral motion under dynamic loading, angular stones are preferred to naturally rounded stones. If ballast particles are bigger than the specified maximum size, the subgrade will be inadequate to distribute the load appropriately. However, too many small stones below the specified minimum size will obstruct the voids and decrease its drainage characteristics in the longer term. No more than 3% by weight should be retained on the 50 mm square mesh sieve and no more than 2% should pass through the 28 mm sieve [3] [5] [6].

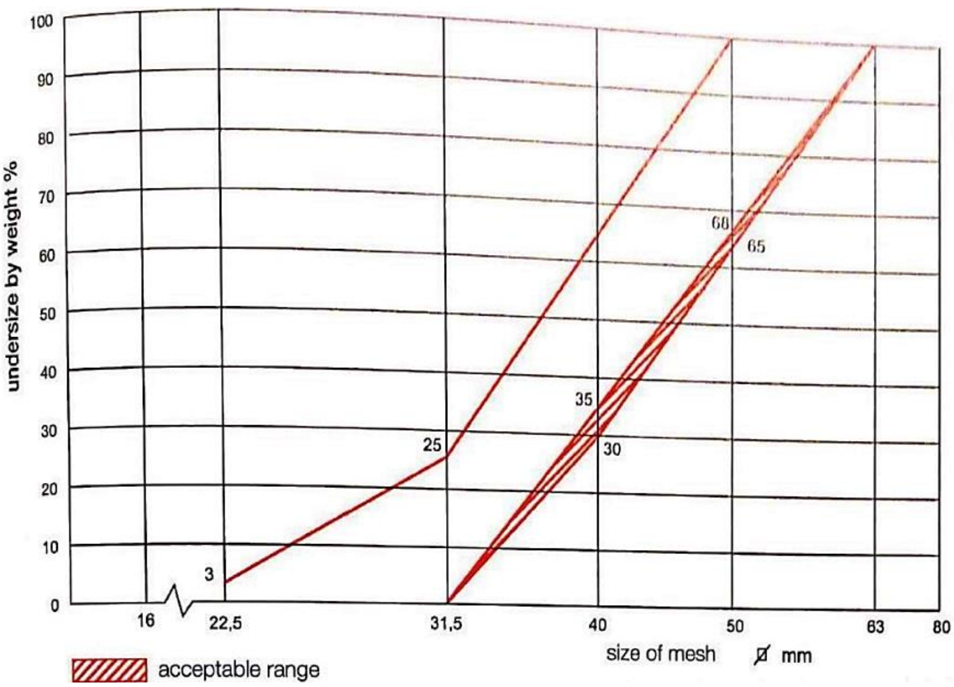


Figure 6 - Permissible range of particle size in the material supplied 22.4 / 63 mm

Ballast stones transfer loads from contact points into an area, big enough to allow subgrade to withstand. It is also important that it's resistant to weather conditions, strong enough and able to be used as drainage for the water. As can be seen in Figure 7 below, due to the random arrangement of ballast stones, vertical force is transmitted by only a few stones, and many stones remain almost unloaded.

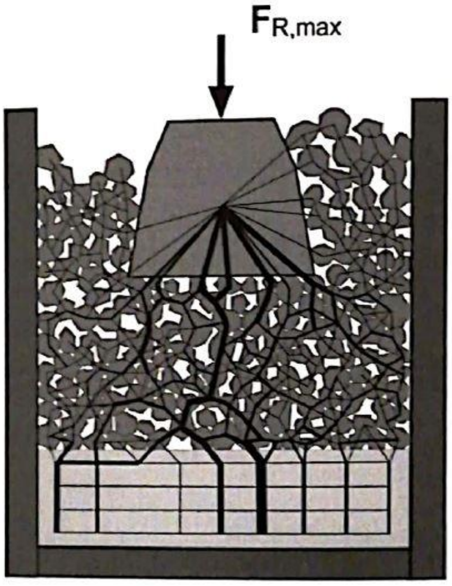


Figure 7 - Contact Forces Between the Ballast Stones [5]

Ballast bed must provide the following functions [5] [8]:

- To transfer the loading from sleepers to soil,
- To restrain the sleepers from vertical, lateral, and longitudinal forces from the rails,
- To enable corrective actions in the track (tamping and lining),
- To ensure track elasticity to minimize dynamic forces,
- To reduce the pressure from the sleeper-bearing area to a level that is acceptable for the underlying materials,
- To provide enough voids between particles to allow an efficient migration of unwanted fine particles from the ballast section.
- To provide an amount of resiliency to the track in order to decrease rail, rail component, and wheel wear,
- It offers the track a good drainage.

The thickness of the ballast bed should be such that the subgrade is loaded as uniformly as possible and, should be at least 25-30 cm for axle loads of 220 kN, a sleeper space of 60cm and a sleeper width 28 cm. For high-speed lines a thickness of 40 cm is recommended. It is also important to provide 45 to 50 cm of ballast width at the sleeper ends to avoid lateral displacement [3] [5].

Index tests must be established for characterizing the ballast properties. These tests evaluate the material's properties such as mechanical strength, shape, water absorption, specific gravity, surface texture, particle size and breakdown from cycles of freezing and thawing. To ensure the supplied track ballast is ready for use, following properties must be proved [5] [8]:

- The ballast must be resistant to weathering
- Water absorption cannot exceed 0.5 percent in weight
- Smaller than 22.4 mm grains have to be less than 2 percent in weight

- The differences between the impact shattering values SD_{10} before and after boiling must not be more than 5 percent in weight
- Its resistance to impact SD_{10} must be ≤18 percent in weight (14 percent for high-speed)
- The resistance to abrasion, according to Los Angeles method, has to be ≤16 percent in weight
- Particles with a maximum ratio of 3:1 for largest to smallest dimensions
- Planar fractured faces intersecting at sharp corners (to give angularity)
- Rough surface texture preferred
- Track ballast must be clean, without extraneous matter such as organic, marl or clay contamination

3.1.1.6. Noise and Vibration

Due to the increase in traffic volumes of both passengers and freights, rail transport systems in recent years have caused concerns among individuals who live alongside the rail tracks and above the metro lines about noise disturbance. Noise is mainly caused by vibrations. These vibrations radiate noise from interaction of the wheels and rail, as well as from other dynamic components like boogie, suspension, engines, breaking systems etc. While noise is unwanted and it disturbs or can even damage the hearing, it also has positive effects such as warning the living being that the train is approaching, or enabling the detection of a component failure via changes in the radiated sound [3] [13].

The track is generally the main cause of the radiated noise for frequencies up to about 2 kHz. Due to the sound absorbing properties, ballasted track has relatively low noise values compared to slab track. Although the main function of ballast is to provide support for the track and drainage for water, as a porous material is used for sound absorption, given that ballast is a porous material, it can be assumed that it has absorptive properties. But it should not be forgotten that good noise absorption can be achieved when the ballast is maintained properly. Ballast crumbles over time due to dynamic loads and a decrease in its performance may be observed [14].

3.1.2. Track Deterioration

Ballast is an abundant material in nature. Beside its mechanical properties' benefits, it is cheap, easy to form and it allows for alignment changes. However, in the long term, under the dynamic loads, ballast breaks down and deteriorates progressively which appears as undesirable changes in track geometry. It settles differently because of weak subgrade and inadequate drainage, gets contaminated due to clay pumping, leads rails to buckle and sleeper breakage occurs due to lack of confining pressure. These track foundation related problems result in expensive maintenance of the rail track including ballast cleaning and replacement [7].

Picture 7 - Track buckles due to lack confining pressures

Picture 6 - Track settles differentially due to weak subgrade

Picture 5 - Track fouls due to mud pumping

Main factors causing degradation of the track performance are listed below [15]:

- Incompatibility of material specification
- High static and dynamic ground stress
- Repeated load
- Insufficient compaction of the soil or loss of soil volume
- Inappropriate, easily broken material selection
- Lack of ballast thickness
- Lack of frequency of ballast treatment and ballast washing
- Poor drainage feature
- High groundwater
- Too small sleepers with insufficient spacing
- Environmental effects such as rain, wind, erosion and vegetation

To overcome or reduce the level of deterioration of track, different mitigation strategies can be applied [7]:

- Better stabilization of the ground
- Track reinforcement using geosynthetics
- Chemical and physical stabilization of formation to increase bearing capacity
- Employing prefabricated vertical drains
- Selection of high-quality ballast with appropriate properties to reduce ballast breakage
- Providing enough confining pressure and using sufficient shoulder ballast

As consequences of track deterioration; rails wear faster, sleepers are overloaded and tend to be broken. Track's damages cause low-speed area and consequently reduce level of service. Track requires more maintenance and component renewal. Lifespan of railway is shortened.

3.1.2.1. Ballast Contamination

Ballast contamination is a major factor of track deterioration in many countries over the world. Contaminated ballast fills the void and effects the drainage performance. Over time, lubricant leakage results in reducing load bearing capacity of the ballast layer. Rainwater washes the polluted ballast layer and may carry hazardous chemicals (mainly Ni, Zn, Fe, Cd, V, Cr, Mn, Cu,) from lubricants into the soil and groundwater [16] [17].

Main sources of ballast contamination are listed below [5]:

- Fines after ballast laying
- Sediments from the air
- Falling of the mines from overloaded wagons such as coat
- Fine particles moving upward from the subsoil
- Vegetation leftovers
- Fines from rail and wheel wearing
- Particles rubbed off during tamping

Biodegradation products from organic plants also seriously effect track stability by sealing voids. Short-root plants bring water and minerals from moist gravels and cover ballast surface. Consequently, fines decrease ballast's shearing strength nearly to round gravel's shearing strength.

3.1.3.Lifespan

As its components are renewed, the service life of the track will extend. Practically, the expected lifespan of the track equals to that of the ballast. There are 4 main components that compose the track. Those commonly used components and their expected service lives are shown in Table 2 below.

Component	Characteristic	Service life [Years]
Rail	UIC 60	28
Sleeper	Pre-stressed mono-block	40
Fastenings	Elastic Type Vosloh W14	40
Ballast	Crushed stones	40

Table 2 - Track components and expected service life [18]

However, it is not possible to accurately determine the service life of ballast material. It depends on many factors such as material quality, maintenance, axle load, weather conditions etc.

Today most of the world’s railways are on ballasted tracks. Even new railways are built with slab tracks, the current asset volume is such that it is unlikely that the dominance of the ballasted track will change in the near future. The ballasted track can be subjected to 10 maintenance tamps throughout its lifetime until it finally needs renewal. Maintenance works are costly operations that take the lion’s share of operational budget. According to 2013 financial report of British Railways Board, Network Rail (UK) spent 42% of its operational budget on track maintenance and renewal. Furthermore, service is disrupted during those operations and additional non-monetized costs are created such as user delay, replacement bus service’s traffic, etc [19].

3.1.4.Maintenance

3.1.4.1. Overview of Track Maintenance

Track maintenance means providing- in the most economical way- maintenance and renewal required for both the railway and its vehicles to ensure that the track meets safety and quality standards. When the decrease of depreciation is outweighed by the increase of maintenance cost, the track can be said to have completed its service life. Table 3 below summarizes the main maintenance operations and approximate repetition periods [3] [5] [20].

Maintenance Operaitons	Cycles [Year]
Tamping	4-5
Grinding	1-3
Cleaning	12-15
Rail replacement	10-15
Sleeper replacement	30-40
Rail fastenings	10-30
Replacement of ballast	20-40
Soil rehabilitation	>40

Table 3 - Cyclic maintenance operations

The different track components and their interactions with each other can change the duration of maintenance requirements. Particularly, because of the unpredictable behavior of the soil, maintenance operations should perform according to observations and measurement devices. To predict the maintenance cycle of the entire track, degradation trends of the specific section as well as a single component can be monitored [20].

Within the scope of this thesis, main attention will be given in for ballast maintenance in the following chapters.

3.1.4.2. Ballast Treatment

Shearing strength is one of the most important features of the ballast. The ballast bed's carrying capacity depends on its shearing capacity. Shearing stress is taken by resistance force due to interlocking contact acting between ballast particles. The angle of internal friction determines the increase in shearing strength. In order to obtain higher shearing strength, friction angle should be high as well. Table 4 shows the relationship between friction angle and shearing strength with respect to roughness of the particles. If the shearing stress gets ahead of the strength, then the ballast starts to break and begins to slide [5] [21].

Description	Proportion of interlocking contact c' [N/cm²]	Inner friction angle Φ[°]	tg Φ
Fouled Ballast	5,2	57,7	1,58
Cleaned Ballast	8,1	63,4	2,00
Round Gravel	4,2	57,4	1,56
Processed Ballast	9,2	65,2	2,16

Table 4 - Relationship between shearing strength and friction angle [5]

3.1.4.2.1. Ballast Cleaning

Fouled ballast causes the geometric deformations within a short time due to lack of shearing strength. This increases the track geometry maintenance operations. In such a case ballast cleaning becomes a more economical solution. As well as the entire ballast bed can be cleaned, only shoulders can be cleaned. This application does not improve the durability as much as when the whole system is cleaned. But, for instance, it saves time until the track system can be renewed. During the cleaning process, undercutter cleaners are used to plough the ballast to the side. The disadvantage of this technique is that it damages sleepers and plows ballast into the track's shoulders and impacts the drainage adjacent to it. During the cleaning process ballast can also be washed with high pressure nozzles. Safe train passages are possible immediately after the cleaning operation. [5] [22].

Picture 8 - ballast cleaning system for TGV lines, France

Ballast cleaning is appropriate if the ballast contains more than 30 percent of fines of less than 22 mm size. It is absolutely necessary when there is more than 40% pollution [23].

3.1.4.2.2. Ballast Profiling and Stabilization

After ballast cleaning, following steps must be ensured to be able to travel at full speed [5]:

- Fixing track design position
- Profiling ballast bed cross-section
- Consolidation of the ballast
- Stabilization of the track

The correction of ballast profile is important to keep the track away from buckling. Additionally, if this maintenance work does not perform regularly, huge quantities of ballast could be lying unused in the track network [3]. Ballast profiling is followed by stabilization with the "Dynamic Track Stabilizer" machine to avoid initial and irregular settlement of the track. This machine simulates the effect of running approximately 700,000 to 800,000 gross tons of operational rail traffic to perform a uniform initial settlement [22].

3.1.4.2.3. Stone Blowing

Track vertical geometry is traditionally adjusted by tamping. However, during tamping operation, ballast could be damaged and become finer particles. British Rail has developed an alternative technique called "stone blowing" in the early 1980s to overcome the drawbacks of tamping application. The approach is the insertion of new ballast under the low sleepers, to recover the level of the track, leaving the body of compact and stable ballast bed undisturbed. Tests showed that although productivity is slower, this technique causes a lower rate of track degradation than tamping [24].

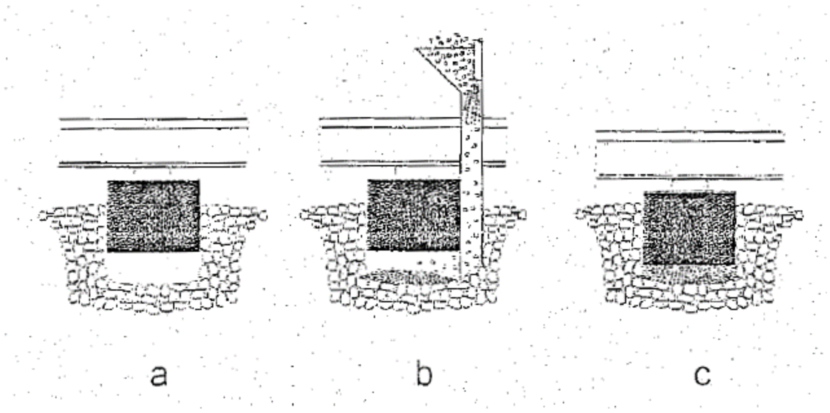


Figure 8 - Principle of stone blowing [3]

3.2. Slab Track

The track system to be applied cannot be determined only based on investment cost, axle loads and speed. The service life, the type and the amount of maintenance, local conditions, and availability of basic materials also should be considered. The main purpose is to provide continuance of the system as much as possible with the minimum cost. When all these factors are considered, slab track systems become a very competitive alternative.

The increase in axle load of freight trains, increase in demand for passenger and competition with other transport means creates bigger traffic volumes day by day. This increased traffic causes faster track deteriorations and requires more frequent maintenance. Therefore, the railway sector is seeking for a stronger track structure than the one of conventional track, currently used.

The term "slab track" is used to describe non-ballasted track structures, which may have combinations of concrete slab, sleepers and road pavement, are used where strength and durability are required [25]. In the past, slab track systems were commonly used for light rail transit. But in last decades, as a result of higher demand for high speed and heavy freight trains, slab track use has increased.

Although the use of slab track is still at a moderate level, a large number of projects are being developed all over the world. The major advantages of slab track systems can be summarized as follows:

- Lower structure height
- Less maintenance requirements
- Longer service life
- High resistance to lateral forces
- No damage or speed limitation due to flying ballast issue

According to the available bibliography, the current lengths (km) of constructed different type of slab tracks are shown in the following table. In chapter 3.2.5, these systems are classified and some of them are analyzed in detail.

Slab Track Design	Country of design	Total construction (km)
Bögl	Germany	4391
Shinkansen	Japan	3044
Rheda	Germany	2205
Sonnevile-LVT	Swiss	1031
Züblin	Germany	606
Stedef	France	334
Infundo-Edilon	Netherlands	211
ÖBB-Porr	Austria	122,2
IPA	Italy	100
PACT	UK	95,4
SATO	Germany	35,8
FFYS	Germany	33,1
BTD	Germany	32
ATD	Germany	31,7
Getrac	Germany	15,3
Walter	Germany	9,4
FFC	Germany	1
Heitkamp	Germany	0,39
BTE	Germany	0,39
BES	Germany	0,39
Lawn Track/Rasengleis	Germany	0,39
Hochtief	Austria	0,39
Deck Track	Netherlands	0,2

Table 5 - Total length of different type of slab track around the world

3.2.1.Track Structure and Requirements

The first applications kept the sleepers and replaced only the ballast with a concrete slab laying on asphalt or concrete sublayers like the road pavement layout. The sleepers gradually became part of the slab, which could then be prefabricated. The sleeper was eliminated in more revolutionary designs. Even more radically, the rail could be embedded into the slab [26].

The condition of the soil plays a fundamental role in the track design selection. Each slab track system has distinct flexural stiffness, which should be calculated according to soil circumstances, since the entire structure depends exclusively on its ability to bear. For instance, if the soil is weak in terms of bearing capacity, the system should have high flexural stiffness in order to act as bridge across weaker locations and local deformations in the substructure [3].

Slab track structure consists of (top-down) [27]:
- track superstructure:
    • rails,
    • fastening of the rails to the rail support,
    • rail support (sleepers, single supporting points, pre-fabricated or monolithic slab),
    • concrete bounded foundation layer (CBL) or asphalt bounded foundation layer (ABL) depending on use of sleepers,
    • hydraulically bonded foundation layer (HBL),
- track substructure (if slab track construction is built on earthworks):
    • frost protective layer (FPL),
    • subsoil layers (consolidated or improved material of earthworks in the embankment or earthen cut),
    • consolidated soil or bedrock.

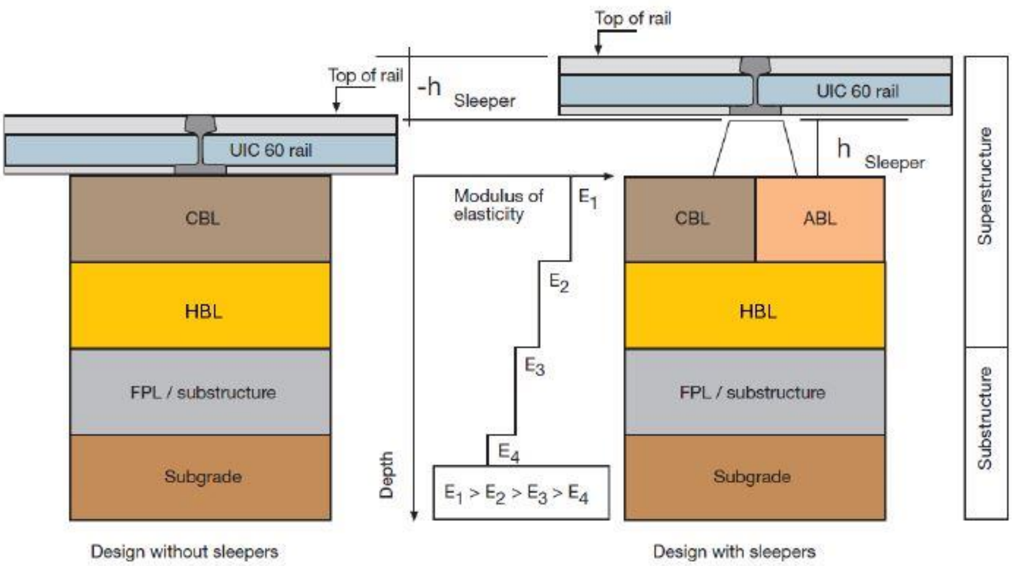


Figure 9 - General construction cross-section of slab tracks [28]

Up to now, the design of slab track systems seems to have focused mainly on the design of the track slab system itself, whereas the design of the foundation slab, as well as the layers below, followed general platform design rules. Special building methods for slab track building were created for both the so-called "top-down" method used, for instance, for the Rheda model or the bottom-up approach (for instance, Bögl system) [26].

Transitions between the slab and ballasted track are still an open question for understanding the behavior of the transition zones. There have been practical alternatives put forward. However, scientifically supported improved designs are yet to come. [26].

3.2.1.1. Subsoil Settling

In comparison to ballasted tracks; slab track systems are much stiffer. Thus, slab track requires a subsoil which is essentially free of deformation and settlements since the adaptability of slab track to settlements is relatively low. Ballasted track can tolerate settlements up to 2 cm over a track section length of 10m and these settlements can be easily compensated by special track machines. Since the changes in the track geometry after construction are limited, such adjustments are almost impossible for slab track [3] [5].

Earthworks must ensure the substructure of the ballasted track is at a depth of 0.5 m below the frost protective layer. This depth is at least 2.5 m below the foundation surface for the slab track. For the designer of the slab track, therefore, it is a challenge to figure out the appropriate and adequate earthwork construction system. The restrictive requirements in earthworks construction lead to higher construction and material costs. In exchange, when designed in a suitable manner, slab tracks provide enhanced lifetime and reduced maintenance costs [5] [29].

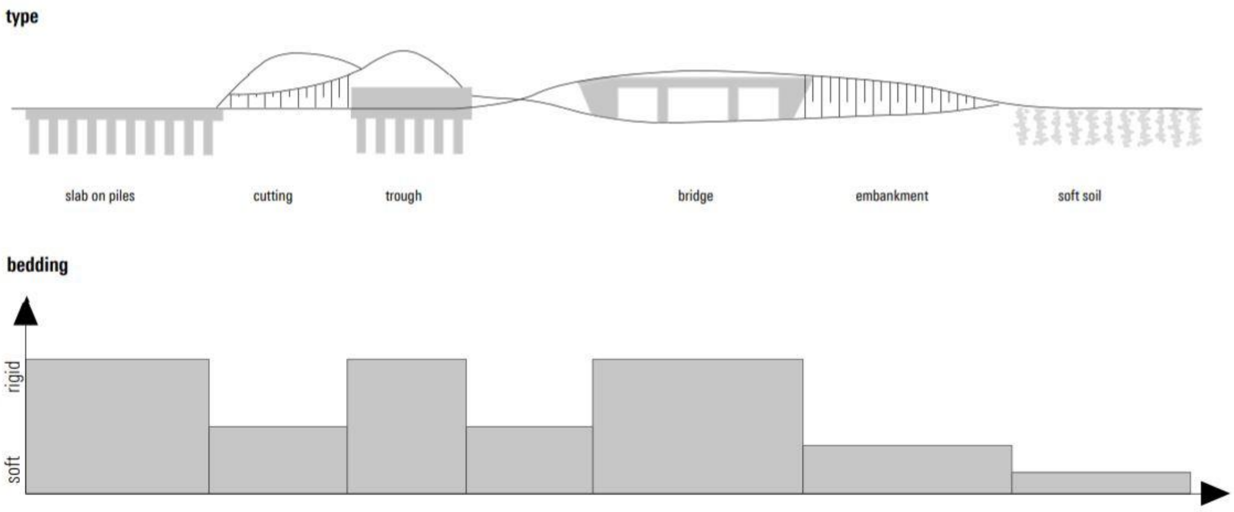


Figure 10 - Different slab track constructions with varying bedding modules [29]

The transition between slab track segments and different vertical bedding modules, such as rigid bridges to soft earthwork constructions (Figure 10), is particularly important. These transitions constitute a critical discontinuity of a path without ballast.

In the case of soft soil, it is necessary to take appropriate measures by different methods of compaction to improve the subsoil. It is possible to improve the soft subgrade by compacting the soil. The use of CFG (cement, flue ash and gravel combination) columns is an alternative solution (Figure 11). Soft soil nearby sensitive structure or under-construction buildings can be enhanced by this method without applying expensive reinforced piles solutions [29].

In challenging geotechnical and hydrological circumstances where other measures are not feasible, time-consuming or too costly to be implemented, there is a need for very particular design methods. It is possible to design the slab track on piles to prevent the issue of long-term settlement and unknown consolidation behavior. The superstructure of the track is supported by a reinforced concrete slab based directly on piles (Figure 11). The loads are distributed through the slab track, then transferred to the piles through the concrete slab. There is no effect caused by the unstable subsoil that acts as filling material. With almost no settlement, this kind of construction is very rigid. The system selected is fully independent from the quality of the soil used in the sub-grade. The construction is therefore similar to bridges regarding settlement and stiffness [29].

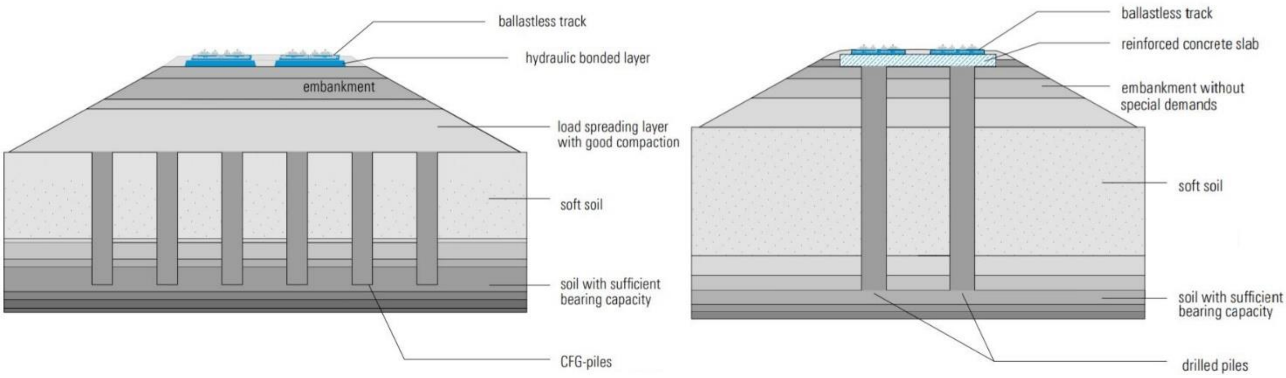


Figure 11 - CFG application on the left, pile application on the right [29]

Differences in settling for a small range, between + 26 and -4 mm, can be compensated by rail fastenings (by inserting different thickness rail pads). It is possible to correct the lateral position within a range of 0-9 mm. But there are currently only a few techniques to evaluate the conduct of long-term settlements. Experience gained in slab track is still not enough to have a clear idea about their settlement behavior. Knowledge in road construction shows that high embankments can result in a higher value of settlements [5].

3.2.1.2. Concrete Foundation Layer

According to Lichtberger, the concrete foundation layer should satisfy the following features [5, p. 297]:

- The required profile tolerance on the surface of concrete bearing layer is $\pm$ 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 180mm should be observed.

3.2.1.3. Asphalt Bounded Foundation Layer

Some important features about the characteristics of the asphalt bounded foundation layer are [5, p. 298]:

- 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 $\pm 2\ mm$.
- 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.

3.2.1.4. Hydraulically Bounded Foundation Layer

Hydraulic bound layer is a stabilized soil between the froze protection layer and slab track which bear the load applied on the track. HBL is a cement bounded layer that contains binders made from cement, lime, gypsum, granulated blast-furnace slag, air-cooled steel slag, or coal fly ash. Since they set and harden in the presence of water, these binders are known as hydraulic binders. This soil stabilization method is already used in pavement design and it has been proved to be efficient [30].

Some key features of this layer are the following [5, p. 298]:

- The typical thickness of the layer should be 300 mm.
- A mix of mineral aggregates is used such as sandstone, crushed sand and stone chips. The maximum grain size should not exceed 32 mm.
- Portland cement is used as bonding agent, and its content is around 110 Kg/m3.
- The hydraulically bonded layer should contribute to achieve a modulus of deformation of $Ev2 \geq 120\ N/mm2$ on the top surface of the frost protection layer.

3.2.1.5. Frost Protective Layer

According to Lichtberger, the frost protective layer also serves to compensate the differences in stiffness of the various layers to the subsoil. It consists of the fine gravel which is resistant to weathering and frost. Its capillary-breaking property has to prevent water rising from the subsoil. Furthermore, it has to lead surface water away rapidly. For this purpose, values of permeability between $1 \cdot 10^{-5} m\,/\,s$ and $1 \cdot 10^{-4} m\,/\,s$ are required. A modulus of deformation $E_{v2} \geq 120\ N/mm^2$ is required for new track and $\geq 100\ N/mm^2$ for upgraded track [5, p. 298].

3.2.1.6. Sound Protection

One of the significant drawbacks of slab track is noise. Increases in noise level are discovered in comparison to ballasted track between 2 and 4dB. The reason for this is that the provided acoustic absorption by ballast was lost. This is probably only about 1dB of the difference, however, a more important factor which causes noise is fastening systems. Slab track generally uses softer rail fasteners. In order to compensate the loss of vertical compliance usually provided by the ballast layer, they are designed to replace additional compliance in the rail support. Therefore, soft rail fasteners can cause rail noise as the rail can vibrate at a longer length [31].

Rolling noise becomes predominant when the train speed reaches about 300 km/h. It starts at the contact area between wheel and rail due to the surface irregularities and it is propagated along with the track components. Additionally, there are other sources that create noise such as aerodynamic noise, impact noise at transitions and traction power noise. The sum of these noises can reach up to 20dB. Regular application to mitigate the noise are rail grinding, rail lubrication, track alignment maintenance, use of resilient rail pads. Concrete slab track and rail pads reduce some noise frequencies but may reflect other frequencies and this issue requires more specific design and maintenance of slab track [25].

Some acoustic treatments have been demonstrated on slab tracks in Germany. As it is shown in Figure 12, full application may lead to noise reduction up to 6dB. Removing the raised barriers reduced it to nearly 4.5dB. A more limited absorptive treatment, leaving the rail uncovered, provided about 3dB of noise reduction. This is enough to make the slab track equivalent to a conventional track with concrete sleepers [31].

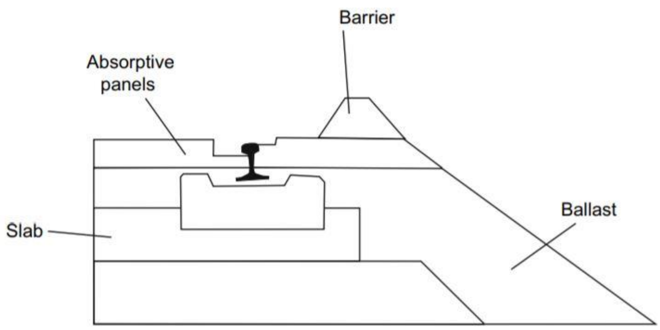


Figure 12 - Absorptive panels on slab track for noise mitigation [31]

Also, different configurations were tested such as absorptive panels on top of the slab track and mini-barriers on both sides as shown in Figure 13. The mini-barriers come to a height of 0.7 m above the top of the rail. They are constructed of concrete elements with a layer of rockwool and an absorptive top layer. These mini-barriers gave a reduction of 6 dB and the absorptive panels on the track slab a reduction of approximately 2 dB in the overall noise. [31] However, many experiments either did not show the required lasting stability or were much too expensive [5].

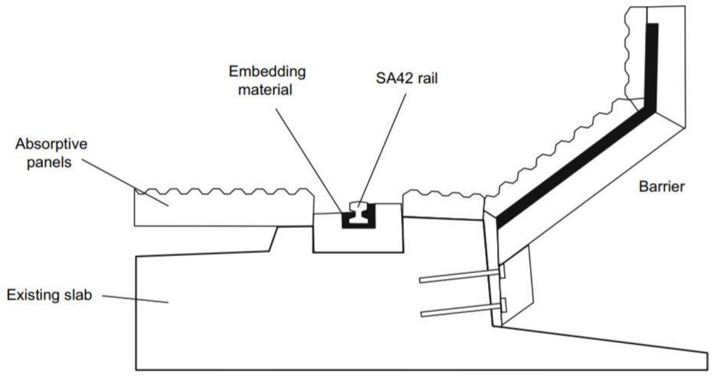


Figure 13 - Absorptive panels combined with mini-barriers [31]

3.2.1.7. Transitions Between Slab Track and Ballasted Track

The superstructure of slab tracks has a significantly greater vertical rigidity compared to traditional ballasted tracks. At the places where two systems meet expose higher dynamic forces to both vehicle and the track, to ensure excellent riding comfort and prevent damage related to dynamic effects, appropriate transitions from slab track on bridges to adjacent slab track on grade, cuttings, and tunnels or even ballasted track sections must be designed.

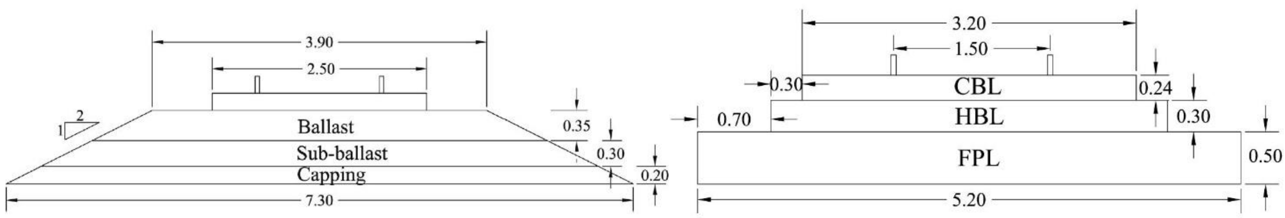


Figure 14 - Ballasted track section on the left, slab track section on the right [32]

Material	Density (kg/m3)	Young's modulus (GPa)	Poisson's ratio (-)
Rail	6186	210	0.3
Rail pad	1950	0.21	0.3
Ballast sleeper	2054	30	0.2
Slab sleeper	2400	70	0.2
Ballast	1800	0.2	0.1
Sub-ballast	2200	0.3	0.2
Capping layer	2200	0.4	0.2
CBL	2400	34	0.2
HBL	2400	5	0.2
FPL	2400	0.12	0.2
Subgrade layer 1	2000	0.05	0.34
Subgrade layer 2	1950	0.087	0.3
Subgrade layer 3	1950	0.21	0.3

Table 6 - Material properties of tracks [32]

The immediate conversion between systems and discontinuity of support material cause variation in the stiffness of the track that leads to irregularities of track level. This area is known as the transition zone and they are the main concern because, often additional maintenance is required to conserve track level and ride quality. This additional maintenance raises the cost of operation and ultimately creates delays in railway track operation.

To mitigate abrupt change of the stiffness in the transition zone, some countermeasures have been offered by researchers such as installing auxiliary rails, gradually increasing the length of the sleepers in transition area, and partially replacing the subgrade with stiffer soils [32].

Auxiliary rail

In this technique, the extra rails enhance the bending stiffness of the track in the transition area and help to transmit the loads better to sleepers and thus reducing ballast stress. During this implementation, some of the actual structural components must be neglected or modified accordingly. For instance, base plates have been neglected and the auxiliary rail is directly attached to sleepers without intermediate elements. 20 meters of the 30-meter auxiliary rail is mounted on the ballasted track and 10 meters on the slab track. Additional rails have the same characteristics as the main rail, with a range of 450 mm from each rail to the nearby main rail [32].

Picture 9 - Implementation of auxiliary rail (Rheda-system) [33]

Longer sleepers

The system is originally designed for the German ICE train network. Over the years, it has been performed successfully, and it is still used widely around the world.

The length of the sleeper has increased gradually in three phases and each phase has four sleepers of same increased length. In each phase length of increments are 3.05 m, 3.35 m and 3.65 m, and no change has been made to the distanced between sleepers or the geometry of embankment. Below, Figure 15 illustrates general concept of this implementation [32].

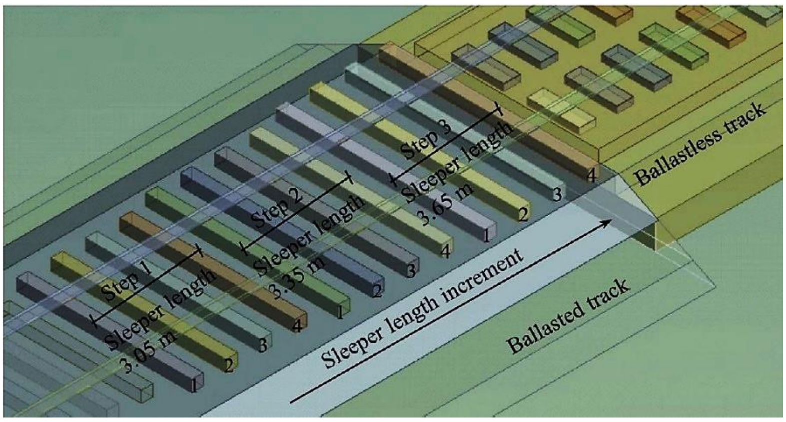


Figure 15 - Transition zone with gradual sleeper length increment [32]

Improved subgrade transition zone

The subgrade transition system is mostly constructed in bridge approaches. The transition zone provided with two different layers consists of Group A & B Filter and Graded Broken Stones (GBS). The important aspect to consider is that new introductions do not change any superstructure properties in both ballasted and slab track and are provided as an enhancement for the top two subgrade layers [32].

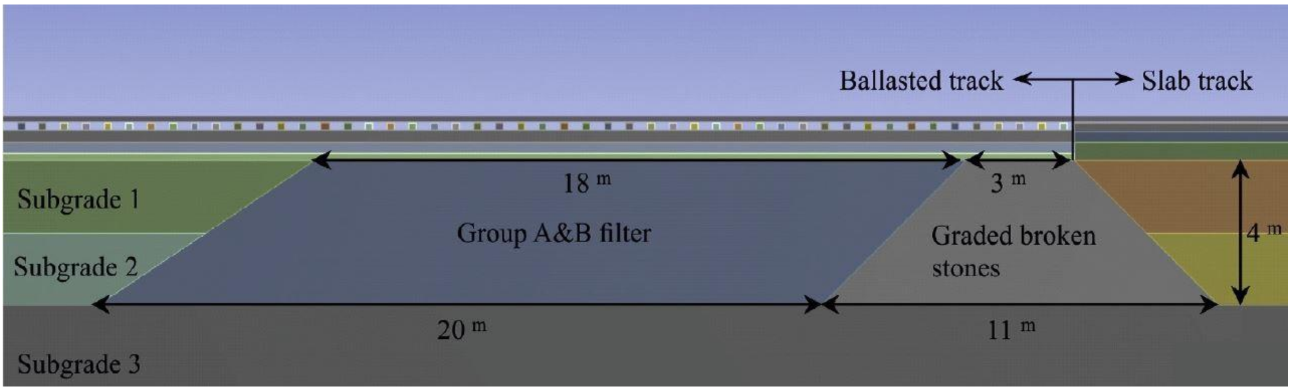


Figure 16 - Improved subgrade system [32]

Material	Density	Young's modulus	Poisson's ratio
Subgrade layer 1	2000	0.065	0.32
Subgrade layer 2	1950	0.075	0.3

Table 7 - Properties of selected materials

The transitions areas usually exist in the following areas:

- At grade – bridge
- At grade – tunnel or trough
- At grade – culverts
- Different types of slab tracks
- Slab track – ballasted track

3.2.1.7.1. Transition at grade – bridge

In order to achieve uniform settlement in the earthwork and in the bridge structure, both should have the same type of foundation. Wedge of soil mixed with cement with content of 3 – 5 % should be arranged behind the abutment of the bridge [29]. There are differences between steel and concrete bridges, however, the solution to select also depends on the bridge length. A transition with a Rheda-system crossing a bridge is given as an example in Figure 17 below [3].

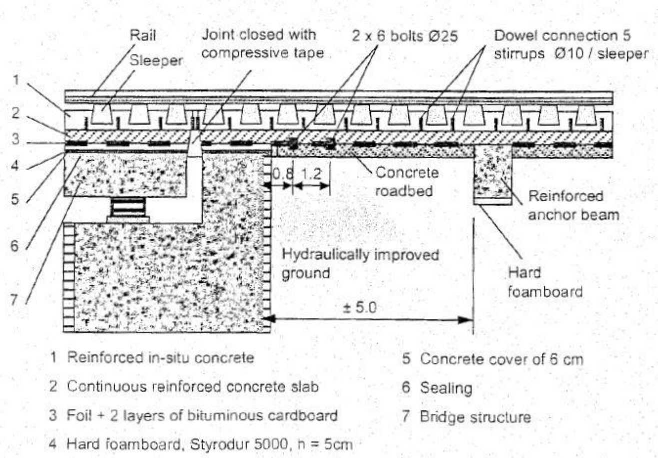


Figure 17 - A transition with an elastoplastic intermediate layer (Rheda-system) [3]

3.2.1.7.2. Transition at grade – tunnel or trough

To decrease the difference in stiffness between the rigid structure and the track laid on subsoil, under the slab track an elastic layer (foam plate) is inserted. The minimum foam plate length is 3.50 m, placed straight in the tunnel or on the trough bottom slab. A wedge made of soil and cement can be implemented depending on the subsoil condition and bearing ability. If the tunnel or trough base is very rigid, a transition area made of concrete is helpful, e.g. based on a pile structure [29].

3.2.1.7.3. Transition between slab track and ballasted track

The transition between entirely distinct track structures must be very smooth with respect to the track systems' significant variation in rigidity.

The following steps are the functional requirements for the transition area to meet [29]:

- The transition to the ballasted track must be carried out under homogeneous subsoil circumstances, with high bearing capacity and good settlement behavior.
- Anchors and dowels are used to form the link between the various bearing layers at the end of the slab track merging into ballasted track.
- In order to rigidify the track framework below the ballasted track, an enlargement of the cement is treated foundation at the end of the slab track. Ballast gluing is to be adopted. The sleepers ' range is restricted to a maximum of 60 cm. Adding extra rails to the ballasted track on a certain length also improves the rigidity.

Additional measures:

- Adapting the fastening elastic characteristics on the slab track.
- Reduction of rigidity on the slab track in fastening points.
- An adoption of abutment structures in the subsoil and an enhanced wedge of soil with cement, the typical soil backfill material mixed with 3-5% of cement.

3.2.1.8. Bridges & Tunnels

Slab Track on Bridges

Bridges are one of the engineering structures that need specific requirements to be considered for slab track implementations.

As a great advantage, bridge structures provide settlement free base, but due to the movements of the bridge, it requires detailed considerations. Variations in temperature cause a longitudinal deformation on the bridge. In addition to this, traffic loads create deflections on the bridge girder. Lastly, creep and shrinkage must be considered. Slab track systems on bridges must therefore be tailored to the specific technical circumstances on bridges. Girder end rotation due to traffic load should be limited to 2 ‰. Uplift forces due to bent rails near the bridge joints must be checked to prevent fastening failure and excess rail stress constraints. It is necessary to absorb longitudinal dilatation without causing elevated longitudinal rail stress. By adapting the transitions layout, high lifting forces in the abutments can be decreased. This can be accomplished by decreasing the distance between the supports or by decreasing the support rigidity. In addition, structural components such as cantilevers or transition girders can be implemented to facilitate the transition [29].

Bridges can be classified in two types: short bridges with a span up to 25 m and long bridges with a span greater than 25 m. In case of short bridges, slab track can be constructed over the bridge without any discontinuity. The system is separated from the bridge by a sliding mat and rigid foam to avoid transmission of longitudinal forces. In case of long bridges, the system has to be fixed to the structure. Design and detailing must comply with the requirements of temperature variation and structural deflection in the joint; attention must be given to temperature gradients, creep and shrinkage. Like bridges with the ballasted track, expansion joints should be intended to absorb longitudinal dilation in the abutments for bridges exceeding a certain expansion length. These expansion joints include, depending on the expansion length and expected girder end rotation, a transition girder as well as a rail joint [29].

Slab track in tunnel

The first slab track application was performed in tunnels. Both the existing rigid tunnel floor and the small building height of the track provide best results for using slab track. In the event of the widening of the tunnel gauge in current structures (for instance, during the assembly of an electrical catenary) a low construction height is a significant advantage. Appropriate geological circumstances are the precondition for the effective completion of the slab track in a tunnel. The rock/soil characteristics must be suitable for the assembly of the slab track. Tunnels could exclude the implementation of plate paths in areas of rockfall or soil with the option of swelling and extension. In general, all structural types of slab track used at grade can also be used in tunnels. The construction of slab tracks in tunnels normally rejects a hydraulic bonded layer; concrete layers are applied directly on the tunnel floor with reduced thickness. In particular, the concrete layer with a grade thickness of 30 cm can be reduced to 15 cm for the use in tunnels.

3.2.2. Track Deterioration

Slab track is designed to need none or very low maintenance during its entire life cycle (50-60 years). Therefore, as in the case of the ballasted track, no major interventions are expected during the service period of slab track. The deterioration of the track geometry may occur only if a sudden and unforeseeable event happens such as derailment. At that point, only very expensive solutions may remediate the damage caused by derailment or environmental influences such as large residual settlements. Dismantling of damaged concrete track and to build new one takes a long time. This means total closure of the line and service disruption. Nonetheless, additional cost arises from substitutional bus services. Appropriate high-level quality assurance measures must ensure the quality of the slab track. This implies additional expense and time for building works and their control. Any deficiency in quality would remain for entire service period and can only be fixed by applying expensive solutions [15]. As an example; due to the on-site completion of the manufacturing process, Rheda System's repairment can result in long line closure. This problem can be overcome by using prefabricated structures such as ÖBB-PORR. According to ÖBB, the track shutdown times are kept to a minimum and the repair or replacement requires very little space so that the parallel track can continue being in operation (except in tunnels). The plates can be easily lifted and replaced within three to four hours.

Picture 10 - Application of ÖBB-PORR System

3.2.3.Lifespan

Theoretically, a concrete track slab is built with at least 60 years of design life. Due to the better track alignment, track components (rail, fasteners, plates, etc.) have longer service life compared to conventional tracks. The first project was put in practice at Rheda, Germany in 1972 and is still in service. Therefore, assuming 60 years life time for slab track system is quite reasonable [34].

3.2.4.Maintenance

Except non- track system cost such as rail grinding, system rarely requires maintenance. According to Austrian Railway Corporation (ÖBB), The oldest section in Austria has been in operation since 1989 without maintenance and service costs [2].

There are different types of slab tracks that require different maintenance operations. These types will be classified in the following section and more detailed information will be given about the most commonly used systems.

[2] Source: http://www.slabtrackaustria.com/fileadmin/content/39_slabtrackaustria/04_download/image_brochure_slab_track_austria.pdf

3.2.5.Classification of Slab Track

Over the years, different types of slab track have been developed around the world. In general, these can be divided in terms of their construction into two groups. Continuous rail support systems are mostly used in tramway. Therefore, it will be out of the scope of this study. Schematically, classification of slab track systems can be seen in Figure 18. Thereinafter, detail information will be given about commonly used systems.

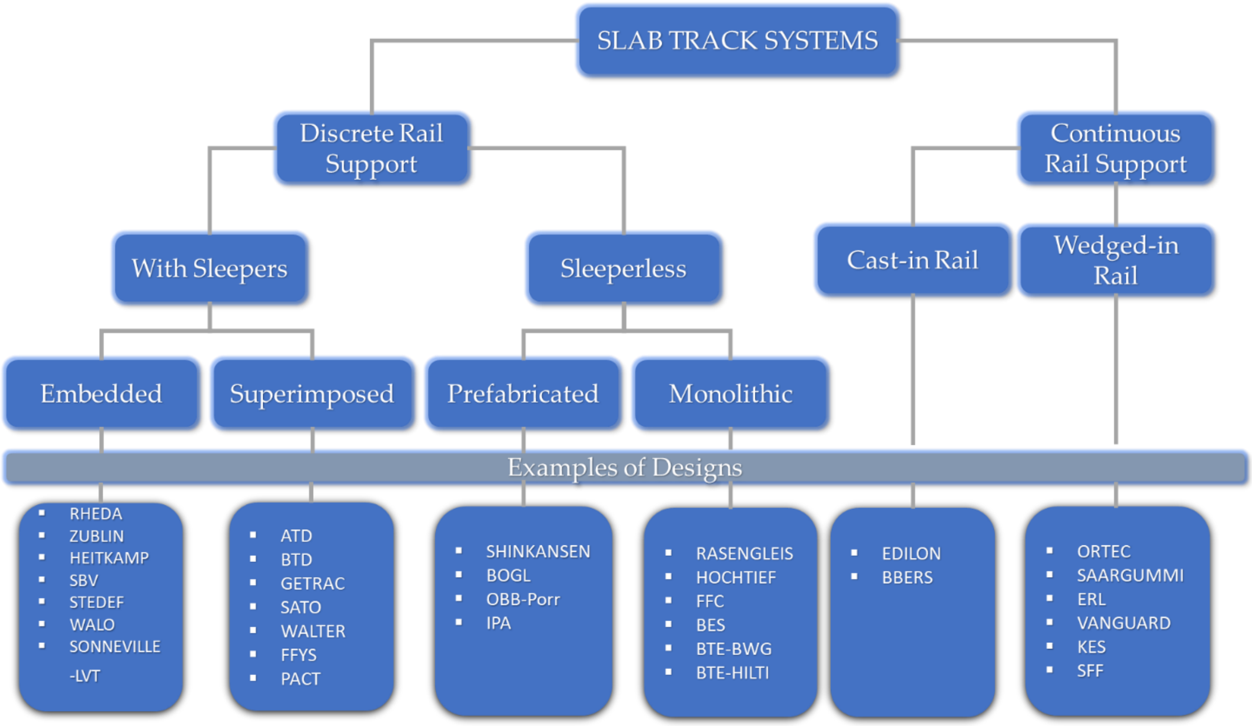


Figure 18 - Classification of Slab Track Systems [3] [5] [30] [31]

3.2.5.1. Sleepers or Blocks Embedded in Concrete

3.2.5.1.1. Rheda System

The basis for the Rheda is a track design first implemented in 1972 on the line from Bielefeld to Hamm, Germany, at a station named Rheda [35]. 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 [5].

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. Following picture illustrates the most significant design versions of the Rheda system.

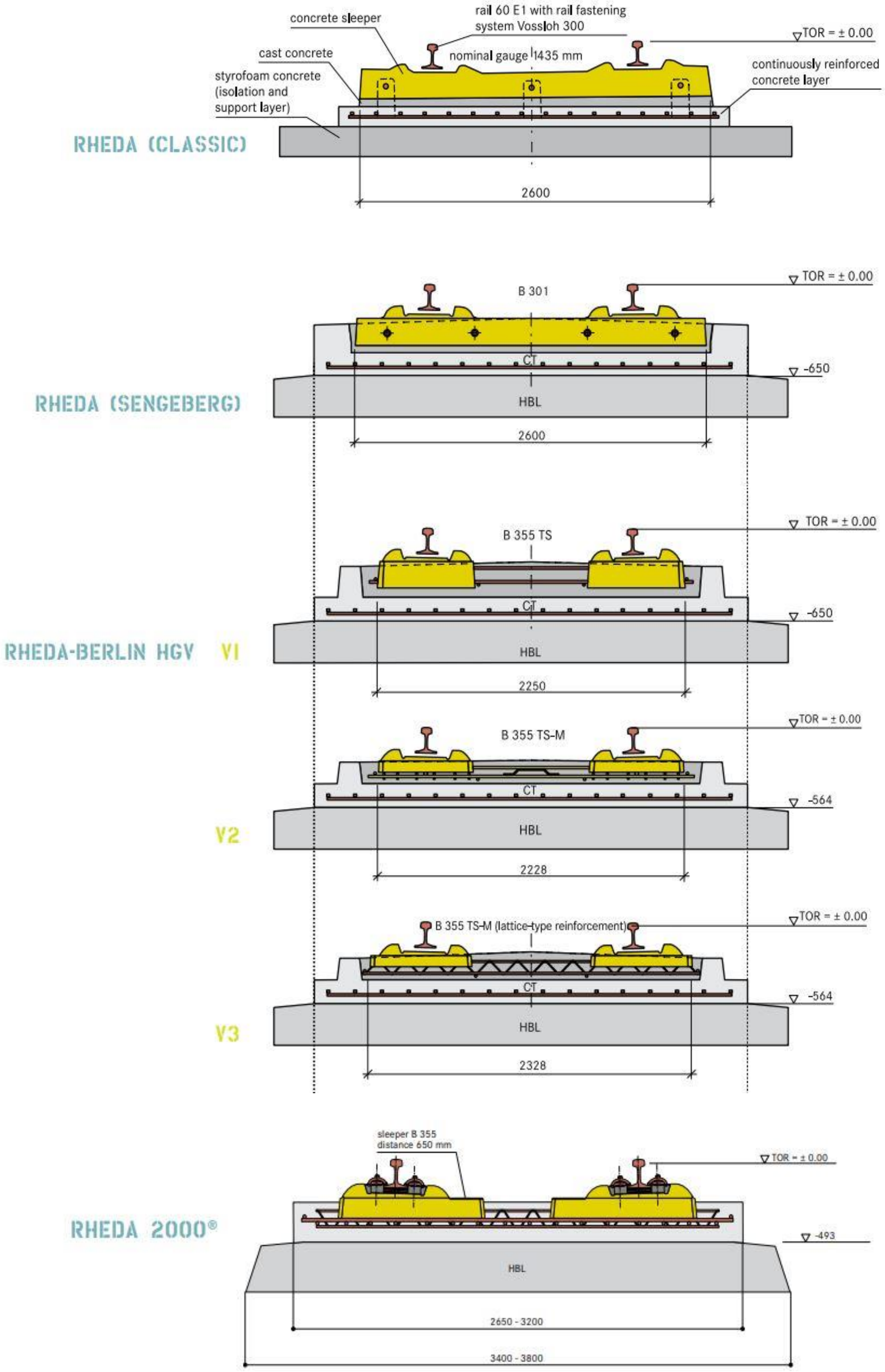


Figure 19 - The stages of development of RHEDA technology [33]

3.2.5.1.2. Rheda 2000 System

The Rheda 2000 Slab Track System has resulted from the ongoing development of the well-known German Rheda system. In order to have a better bonding between the reinforcement concrete foundation and the sleepers, classic mono-block practice was abandoned, the new design uses the twin-block system [3] [5].

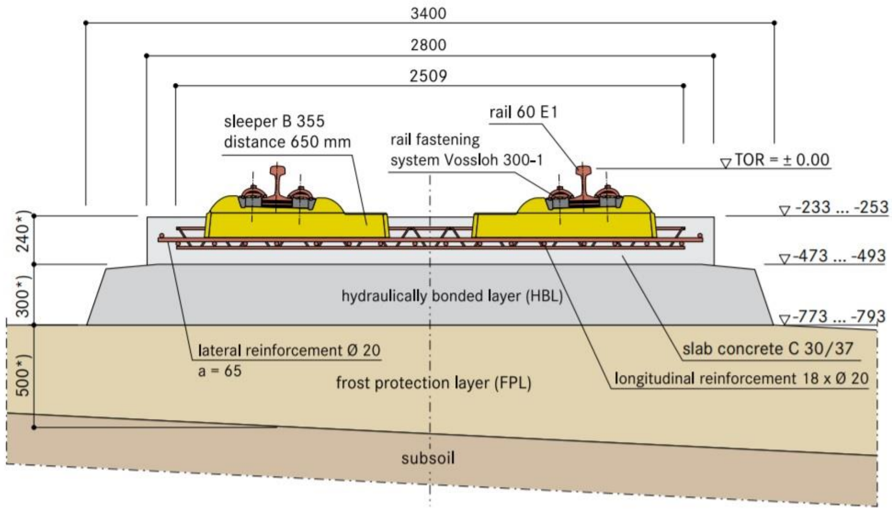


Figure 20 - Rheda 2000 System

Sleeper blocks are connected by untensioned braced-girder reinforcement in the factory. Then the blocks are integrated with longitudinal reinforcement of the foundation area in the site. After that, concrete pouring process takes place. All the elements are cast in concrete in one. The system requires a settlement-free foundation because the purpose of the reinforcements is to transmit lateral forces, not provide a rigid slab. Additionally, the type of fastener used in the system allows compensating for long term substructure settlements [3] [5] [33] [35]. General features of the system are:

- Cast-in-place
- B 355 twin-block sleepers
- The minimum strength of the concrete layer is C30/37 MPa
- Highly elastic Vossloh 300 rail fastenings

Until recently, the system did not require any major maintenance operation. But experience has shown that repairing works take long time and disrupt the service. In case of an accident such as derailment or settlement, remediation works need a complete line closure and a huge investment.

3.2.5.1.3. Züblin System

Züblin track is a continuous monolithic cast in situ concrete slab with embedded by twin-block or mono-block sleepers carrying the rails. It's maintenance free and enables alignments with steeper gradients and tighter curves than conventional ballasted track. The main difference of the system from Rheda 2000 is that requires special equipment and designed machinery for implementation. Thus, approximately 200m can be built in 8 hours shift. Labor cost of the system is significantly lower than Rheda 2000 due to mechanized process.

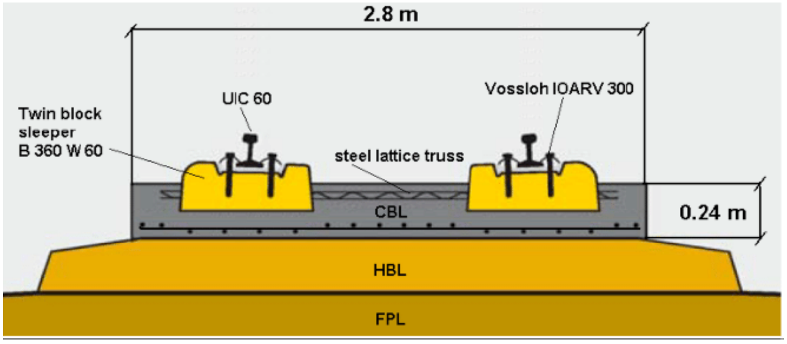


Figure 21 - Recent configuration of Züblin System

Above 50cm frost protection layer, 30cm thick hydraulically bonded layer is built and on top of it, concrete bearing layer are cast with twin-block sleepers. In the Züblin System; firstly, concrete bearing layer is poured and then, sleepers are placed in to the fresh concrete. A special lift lowers the sleeper into the concrete and simultaneously vibrates them. In this way, sleepers are positioned into their exact geometrical position [3] [5] [36].

3.2.5.2. Sleepers Superimposed with Asphalt-Concrete Layer

3.2.5.2.1. Getrac System

The Track System of Getrac is formed of an asphalt base on which concrete sleepers rest directly. Special concrete anchor blocks connect the sleepers to the asphalt layer and transfer the horizontal forces from track to supporting layer. The advantage of the system is that it can be applied with conventional track-laying technology.

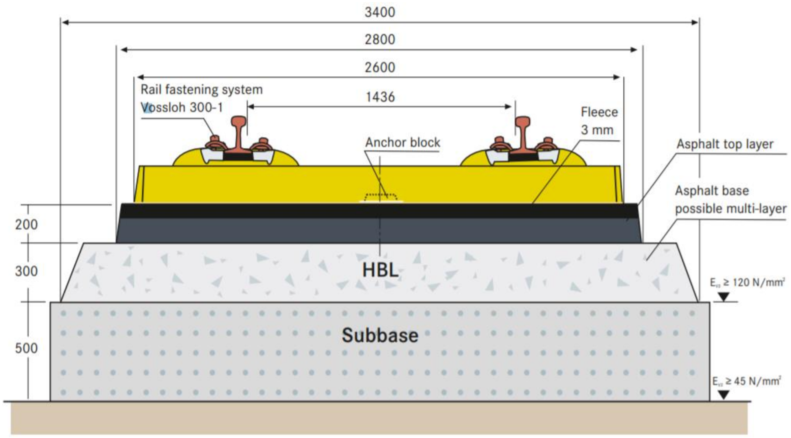


Figure 22 - Getrac A1 Slab Track System

According to Rail One, benefits of the system are listed below:

- Geometrically rigid structure
- Easy and quick installation
- Cost-effective compared to other slab systems

- Easy to renew in case of accident
- Short construction time
- Allows to use conventional road and track's construction equipment
- Highly efficiency drainage
- Suitable also for turnouts and crossings
- Possibility of rail super elevation greater than 180 mm

3.2.5.2.2. Sato System

Picture 11 - SATO Y-shape sleepers

Y shape steel sleepers connect rails on asphalt foundation layer. Sleepers are welded to steel strip in the asphalt foundation layer by using Nelson bolt. In this way, sleepers are fixed in both their horizontal and vertical directions. The system gives good results in test tracks, but it is an expensive application.

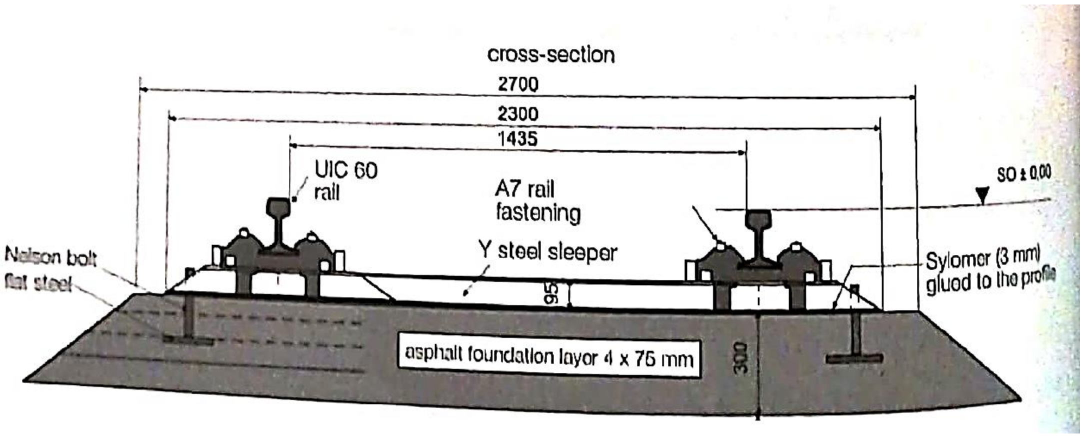


Figure 23 - SATO cross-section

3.2.5.3. Prefabricated concrete slabs

Cast-in-place concrete slab track systems are accepted throughout the world and those systems are applied more widely compared to other systems. Although it has many advantages compared to conventional tracks, system brings along some drawbacks. These are [3] [5] [37];

- It's hard to ensure the same quality in every concrete pouring,
- Curing time of the concrete takes time and limits the construction,
- Due to the exhaust gas of concrete vehicles, workers' health is threatened during the underground or tunnel application,
- Site installation consists of several stages and requires complex workmanship
- It does not require maintenance, but it is hard to repair in case of accident or settlement

Therefore, prefabricated slab track systems become a good alternative to eliminate these shortcomings. General advantages of prefabricated systems are [3]:

- High-level mechanization,
- Lower labor cost,
- Diminish the workmanship fault,
- Slab can be replaced easily if it is damaged,
- Rail can be directly adjusted and fixed.

Prefabricated slabs with direct rail fastening were primarily used on the Shinkansen-lines in Japan and Italy with the IPA system derived from the Japanese. There are also other designs such as Bögl developed by Germany and ÖBB-PORR by Austria. Although the system has many advantageous features, it can be up to 4 times more expensive than conventional system [5].

Comparisons to be carried out in the fourth and fifth chapters with reference to precast systems.

3.2.5.3.1. Shinkansen System

Japan has been a pioneer in the development of high-speed train. The first high-speed train line was opened between Tokyo and Osaka in 1964. This line used traditional ballasted track and experienced difficulties led to the development of Shinkansen Slab Track System [38].

Prefabricated slabs of 5m long are laid on a concrete bed and a 4cm thick cement asphalt mortar is injected under slabs. Each slab has a weight of approximately 5 tones. The dimension of one slab is 2.34m wide and 19cm thick. Low pretension is used in the longitudinal and lateral direction. Between each slab, there is a cylindrical stopper, 400-520mm in diameter and 200mm in height which is rigidly connected with the structural concrete of the foundation to prevent lateral and longitudinal movement. Figure 24 shows the typical structure of Shinkansen Slab Track [3] [5] [38] [39].

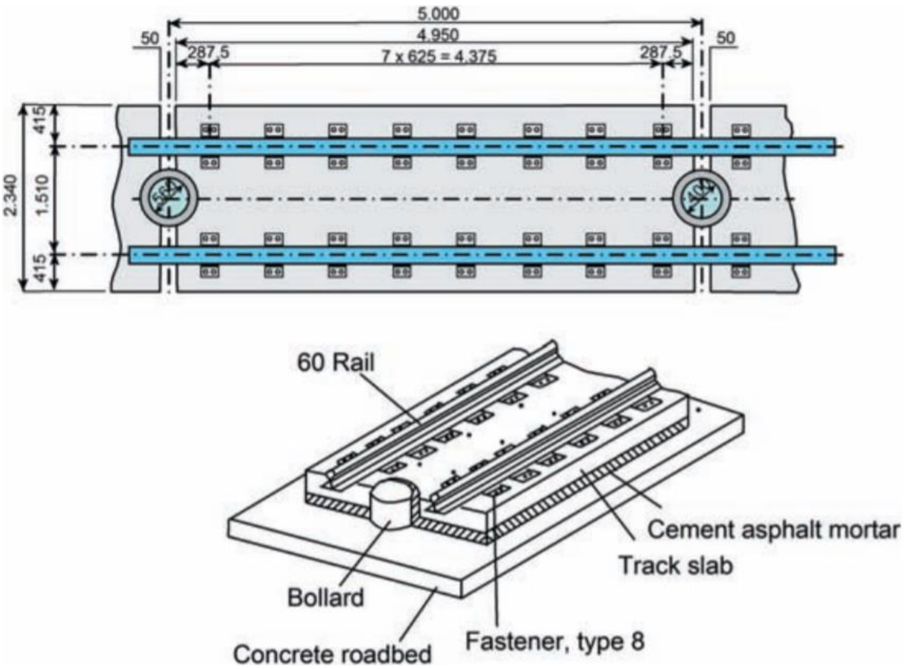
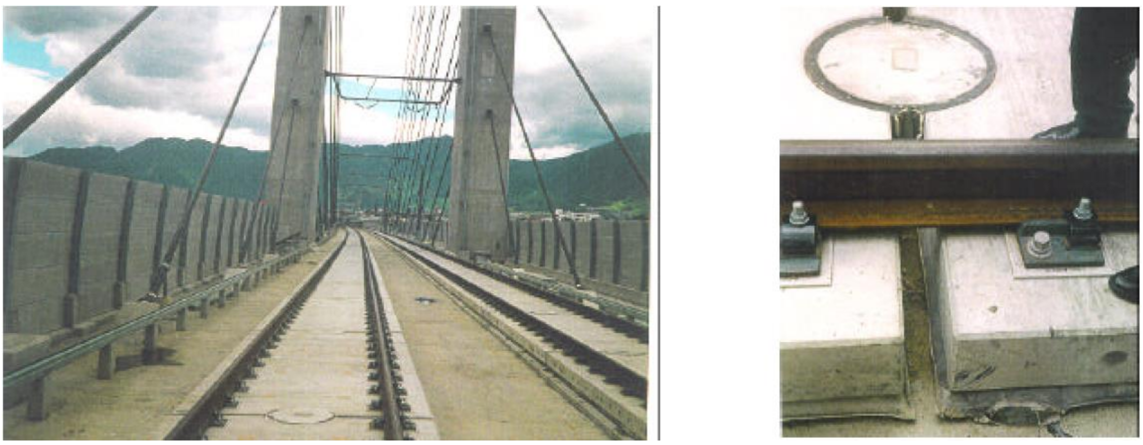


Figure 24 - Shinkansen Slab Track

According to the Japanese National Railroad, the following criteria must be fulfilled to apply slab track [25]:

- Construction cost of the slab track cannot be %50 more than the cost of ballasted track.
- Slab track should have resilience at least equivalent to ballasted track.
- It should be applied for high speed trains.
- Slab track system should be adjustable to compensate for possible vertical and lateral movements due to subgrade settlements.



Picture 12 - Application of Shinkansen System

Except for minor cracking related to alkali-silica reaction and some slab warping in tunnels, the general condition of the slab track is good. On average, the construction cost of the slab is 1.4 times higher than ballasted track. But the higher investment is expected to compensate in 8 to 12 years by low maintenance cost. As seen in the Figure 25, maintenance cost of

Shinkansen is about ¼ of ballasted track. Thus, the slab tracks have made greater contribution to reducing maintenance and labor cost [3] [5] [25] [39].

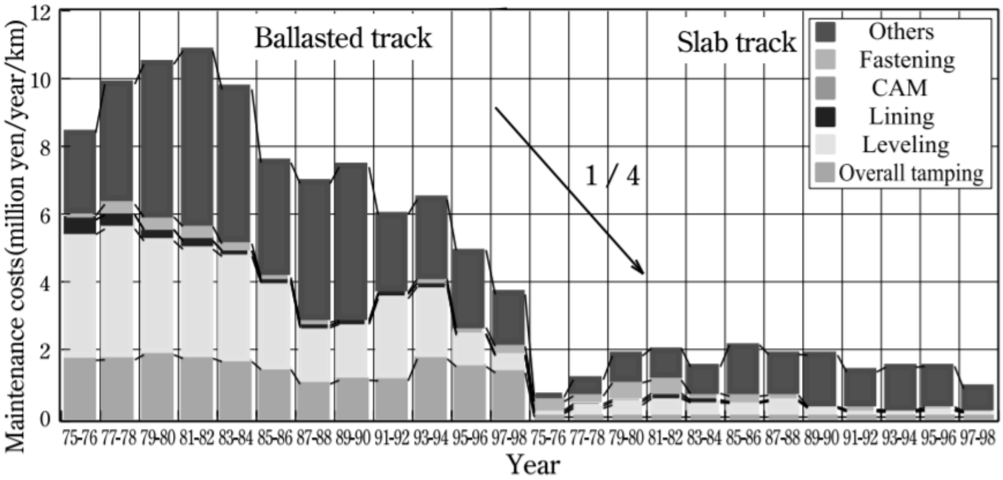


Figure 25 - Maintenance cost comparison between ballast and slab track [39]

3.2.5.3.2. Bögl System

Bögl System shows similarity to Shinkansen System except that it uses C45/55 reinforced concrete and is 20cm thick, 6.45m long and 2.55 or 2.80 wide. The main characteristic of the system is the predetermined breaking points every 0.65cm between the supporting points in order to prevent random crack formation in the slab.

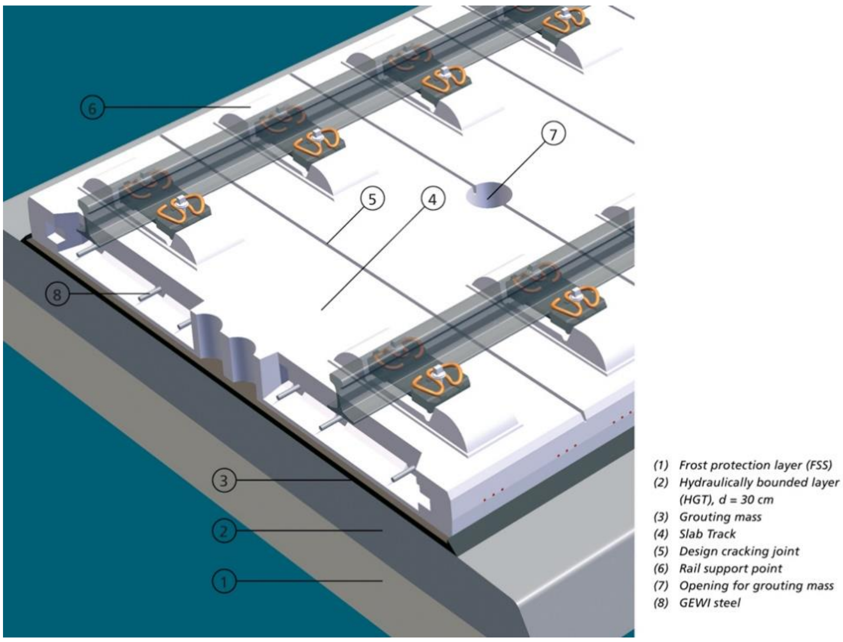


Figure 26 - Bögl System [3]

Comparison to Shinkansen, one of the great advantages is that it can compensate the settlements up to 76mm within rail fastening system [5] (Shinkansen up to 30mm [39]). And

[3] Source: http://www.vde8.de/The-Boegl-ballastless-track-system------_site.site..ls_dir._nav.773_likecms.html

the disadvantage is one slab is about 10t that limits transportation because of the axle-load restriction on the road [3].

Figure 27 the standard cross-section of Max Bögl System. This design gives the most efficient drainage possible particular importance. 5cm of the outer lateral projecting edges of the hydraulically bonded foundation layer where laid below the slab edges. Thus, the water under the slabs is considerably clogged from penetration.

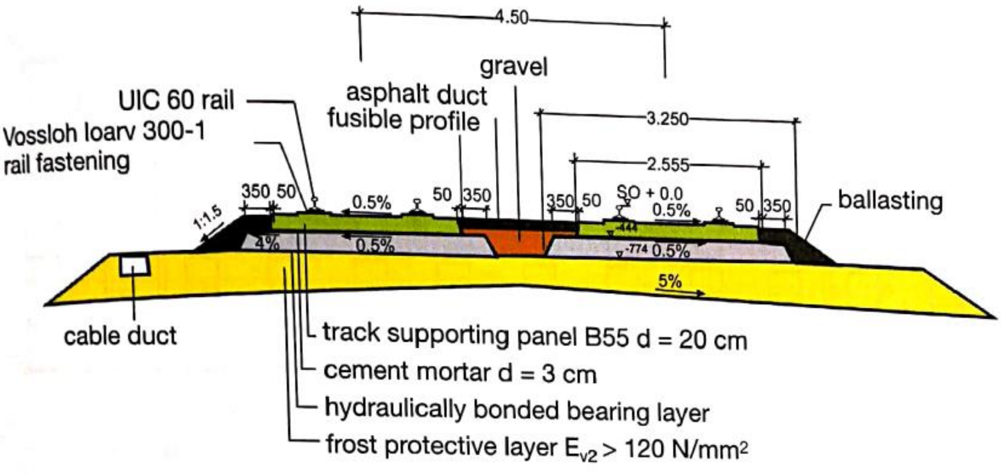


Figure 27 - Cross-section of Max Bögl System

3.2.5.4. Monolithic Tracks

In this system, fastening systems are directly bolted to concrete or steel deck. Use of direct rail fastenings reduce the loads on the surface and eliminate the problems caused by sleepers.

3.2.5.4.1. Pact-Track

Paved Concrete Track (PACT) is a continuously reinforced concrete pavement laid by a specially designed 'slip-form' paver. It has a 22.9 cm thick concrete slab that is 2.43 m wide. Concrete was placed using a customized slipform paving machine, which rode on two 136 RE rails, which were later used for the track [6] [25].

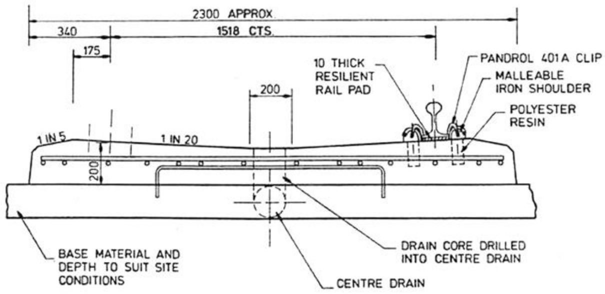


Figure 28 - Cross-section of Paved Concrete Track

The advantages of this system are the low construction costs and the high-quality geometry. This is especially useful in the existing tunnels in the main line size where the shallow construction depth may permit the achievement of increased overhead clearances for 25 kV electrification or for the passage of large container trains. In this track system a great deal of attention needs to be given to drainage channels. The drainage is frequently blocked by the collection of debris that leads to railway fastenings corrosion. Although it was designed for high speed lines, it cannot exceed 150 km/h [6].

4. ENVIRONMENTAL IMPACTS OF RAILWAYS

Railway constructions and operations may cause negative effects that alter the microclimate, soil, and hydrological dynamics as well as natural habitat for many species [40]. Among these, noise and vibration are the most well-known disturbance caused by trains. Soil erosion is another concern that results from the construction of railways [41].

4.1. Main Railway Disturbances

4.1.1. Noise and Vibration Emission

Freight wagons are the main sources of the noise. High-speed and conventional trains follow them respectively. These noises derive from rail/wheel contact, braking systems, gears as well as aerodynamic impacts. Noise above 55 dB(A) is considered as pollution for humans, 65–75 dB(A) cause stress to the body, leading to arterial hypertension cardiovascular disease and heart attacks. [41] Aerodynamics noise becomes effective as of approximately 250 km/h [5]. Measurements on the TGV-Réseau line show that noise emission reaches up to 97 dB while train runs between 250 and 350 km/h [42].

The phenomenon of vibration induced by train can be defined as wave propagation through buildings and soil. Motion of the train on certain locations causes a reaction from surrounding environment. This reaction variety depends on track quality, foundations and vehicle type [43]. Higher the train speeds cause higher vibration frequencies [5].

Vibrations spread through compression waves, shear waves and the surface (Rayleigh) waves, from the track to the ground. The energy of wave decreases with increasing distance from the source. Structures close to the railways are affected by surface waves. The most critical circumstances arise when the predominant soil vibration frequency is the same as the natural frequency of the structure. This may cause serious damage to the structure [3].

The human body is sensitive to the following frequencies of vibration [3]:

- 0.1 – 0.2 Hz: resonance of the organ of balance, resulting in phenomena characteristic of seasickness;
- 4 – 8 Hz: resonance of the contents of abdominal cavity and thoracic cavity;
- 30 – 80 Hz: resonance of eyes in the eye sockets, resulting in loss of focus

4.1.2. Air Pollution

Possible sources of rail-related contaminants include exhalation of diesel fuel, the abrasion of brakes, wheels and rails as well as the transportation of minerals and treated rail sleepers. The main pollutants emitted from the diesel-powered locomotives are carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), nitrogen oxides (NO_x), nitrous oxide (N_2O), sulphur dioxide (SO_2), non-methane volatile organic compounds (NMVOC), particulate matter (PM) and hydrocarbon (HC). Some studies reported higher levels of PM_{10} and

PM2.5 near railways, higher than the standard level allowed for the USA, Europe, and Asia [41].

4.1.3.Soil and Water Pollution

With the increase in the population and vehicles, emissions arising from transportation have become one of the most important sources of heavy metals. Fuel combustion, wheel and track material abrasion, and leaked lubricants containing heavy metals are deposited in the ballast. The ballast is washed with the rainwater and heavy metals pass to the soil and groundwater.

Herbicides and pesticides are other sources of soil and water pollution. To guarantee a minimum level of safety on the ballasted tracks, vegetation should be prevented along the line. Usually, these works are carried out with the help of glyphosate, a moderately toxic herbicide. In March 2015 Health Organization (WHO) declared that it probably causes cancer [4].

4.2. Living World in Ballast

Ballasted track railways create a natural environment in which some plant, insect and animal species can grow, especially some reptile species. Some active lines in sunny areas of large valleys and some large switchyards, as well as unused railways not dismounted, have a particularly high richness of reptiles [41].

Picture 13 - Wall lizard between rail and ballast [5]

Sand and wall lizards are considered threatened species in Europe. Therefore, the maintenance or construction operations on the ballasted track lines endanger the life of these species. Thousands of sand and wall lizards have been seen along the route of the Stuttgart railway project. Deutsche Bahn has estimated the cost of resettling the reptiles at around €15m. The rail company says they have budgeted between €2,000 and €4,000 per creature.

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[4] Source: https://uic.org/projects/vegetation-control-and-use-of-herbicides-348

[5] Source: https://www.lacerta.de/AS/Artikel.php?Article=80

5. COMPARISON OF BALLASTED AND SLAB TRACKS

The conventional track system is a proved technology has developed over the centuries. However, new requirements in railway transportation could not be satisfied with ballasted track solutions. The increase in speed has caused faster track geometry deformations, thus more maintenance works are needed. In addition to this, due to increasing axle load, settlements occur more frequently. Although the major advantage of the ballasted tracks is its low construction cost, the cost of ballasted track in tunnels is higher because here the insertion of matting below the ballast is required. Furthermore, the slab track requires a lower total depth [5] [28].

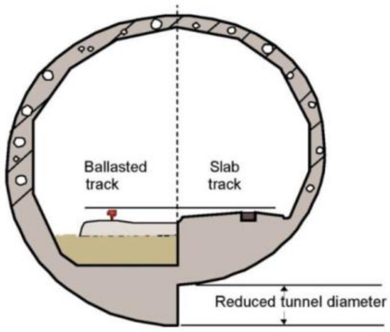


Figure 29 - Reducing cross-section at tunnels

Further advantages of slab track system are more relaxed rules on maximum track super-elevation and super-elevation deficiency values. Another benefit of the track slab is being a simpler and cheaper vegetation control than conventional track control.

On the other hand, slab track radiates higher noise. This means additional costs are required to mitigate the noise. Overall, installing slab track on earth structures, compared to a ballasted track system, is not cost-effective due to high production and implementation costs. But many years of declining demand for maintenance track and elevated operational efficiency in its lifetime indicate that it is more cost-effective in the life cycle [5].

	BALLAST CONSTRUCTION	SLAB TRACKS
SUPERSTRUCTURE	➢ Rails ➢ Rail fastening ➢ Rail Support by Sleepers: - Normal transverse beams - Innovative solutions as frame or ladder ➢ Ballast	➢ Rails ➢ Rail fastening ➢ Rail Support: - Discrete with sleepers or support points - Continuous support with embedded or clamped rails ➢ CSL or ASL ➢ HBL
SUBSTRUCTURE	➢ Upper non-bonded supportive layer, possibly as frost protection layer (FPL) ➢ Lower non-bonded supportive layer: Earth works with compressed or improved embankment or cut formation ➢ Foundation possibly compressed	➢ Upper non-bonded supported layer: frost protection layer (FPL) ➢ Lower non-bonded supportive layer: Earth works with compressed or improved embankment or cut formation ➢ Foundation possibly compressed

Table 8 - Components for ballast and slab tracks construction on earthworks [44]

As can be seen in the Table 8 above, the differences between ballast and slab track construction superstructure and substructure are given. Although the substructure design is similar, different construction methods can be applied in earthworks due to differences in settlement behavior.

To give a general idea, the mutual comparison of the two systems is summarized in the Table 9.

Comparison between Ballasted track and Slab track			
No.	**DESCRIPTION**	**BALLASTED TRACK**	**SLAB TRACK**
1.	Maintenance Input.	Frequent maintenance & non-uniform degradation	Less maintenance for geometry.
2.	Cost comparison	Relatively low construction costs but higher life cycle cost.	Relatively high construction cost but lower life cycle cost.
3.	Elasticity.	High elasticity due to ballast.	Elasticity is achieved through use of rubber pads and other artificial materials.
4.	Riding Comfort.	Good riding comfort at speeds up to 250 – 280 kmph.	Excellent riding comfort even at speeds greater han 250 kmph.
5.	Life expectation	Poor Life expectation. (15-20 yrs)	Good Life expectation. (50-60 yrs)
6.	Stability.	Over time, the track tends to "float", in both longitudinal and lateral directions, as a result of non-linear, irreversible behaviour of the materials.	No such problem.
7.	Lateral resistance	Limited no compensated Lateral acceleration in curves, due to the limited lateral resistance offered by the ballast.	High lateral resistance to the track which allows future increase in speeds in combination with tilting coach technology.
8.	Noise.	Relatively low noise	Relatively high noise and vibration nuisance.
9.	Churning up of Ballast.	Ballast can be churned up at high speeds, causing serious damage to rails and wheels.	No such damage to rails and wheels.
10.	Construction cost of Bridges/Tunnels/etc.	Ballast is relatively heavy, leading to an increase in the costs of building bridges and viaducts if they are to carry a continuous ballasted track.	Less cost of construction of bridges and viaducts due to lower dead weight of the ballast-less track.
11.	Construction Depth.	Depth of Ballasted track is relatively high, and this has direct consequences for tunnel diameters and for access points.	Reduced height.
12.	Availability of Material.	Limited	No problem of material.
13.	Permeability.	Reduced permeability due to contamination, grinding-down of the ballast and transfer of fine particles from the sub grade.	High impermeability
14.	Dust pollution.	Release of dust from the ballast into the environment thus causing environmental pollution.	Less environment pollution.
15.	Maintenance possession	More possession time for routine maintenance	Less possession time but major repair will take substantial time

Table 9 - Comparison between Ballasted track and Slab track [6]

[6] Table source:
https://www.academia.edu/10024210/Comparison_between_Ballasted_track_and_Ballastless_track_No._DESCRIPTION_BALLASTED_TRACK_BALLASTLESS_TRACK

5.1. Ballasted Track for High Speed Lines

The Conventional railway track have numerous advantages such as low-cost construction, good drainage, low noise emission, possibility to change geometry and easy maintenance. However; due to the natural features of ballast material, different settlement behaviors between sections and deterioration are likely to occur. Studies have shown that with the increase of trains axle loads and speeds, dynamic forces increase rapidly, and this reaches critical vibration values. High vibration values speed up deterioration and deformation of track and bring severe safety problems. On the new high-speed ballasted tracks, vibration speed of the ballast of 20 – 26 mm/s were measured. Normal values are considered between 10 and 15 mm/s [5].

"Sunburn" is a phenomenon that occurs to basalt or basalt-related material. After being subjected to atmospheric impact, these materials tend to produce grey-white stains, form cracks that weaken the mineral structure of the material and eventually weaken the entire material. This may occur within a few months, depending on the origin of the rock.

Another phenomenon, ballast-flying, is a major problem caused by high speeds over 300 km/h in terms of safety and of early deterioration of rolling stock and railway. This phenomenon limits the operating velocity of high-speed trains on ballasted tracks [45].

When a train is running at high speeds, a strong turbulent airflow is occurred upon ballast bed due to the boundary layer on the train underneath as well as perturbation by irregular train components such as standing proud bogies. Speed of this airflow can reach up to 50 m/s and it drags the ballast on the track to roll along the track. Dragged ballast does not only cause faster track deterioration but also damages the train. Ballast flight injuries such as damaged wheel, broken glassed at station have been reported frequently [46].

According to the Professor Klaus Riessberger from Technical University of Graz, after many high-speed train applications on ballasted track, the following inferences have been made:

- Uniformity in any respect is a major demand for the use of ballasted tracks for the purpose.
- Extremely prominent is the thickness of the ballast layer and thus the correctness of the top-of subgrade geometry.
- The correct and uniform width of the ballast bed is required for long lasting track stability.
- The stiffness of subgrade should be as uniform as possible.
- Turnouts must be matched into the track in the smoothest manner.
- Interconnections between ballasted track and slab sections (at bridges etc.) must be treated carefully in the engineering process.
- The subgrade must be perfectly drained to avoid any damage by the action of water.
- Track-gauge must be chosen with respect to excellent running properties of the vehicles. Practical experience indicates that gauges below 1435 mm (with standard gauge) can cause wheelset instabilities with high speeds.

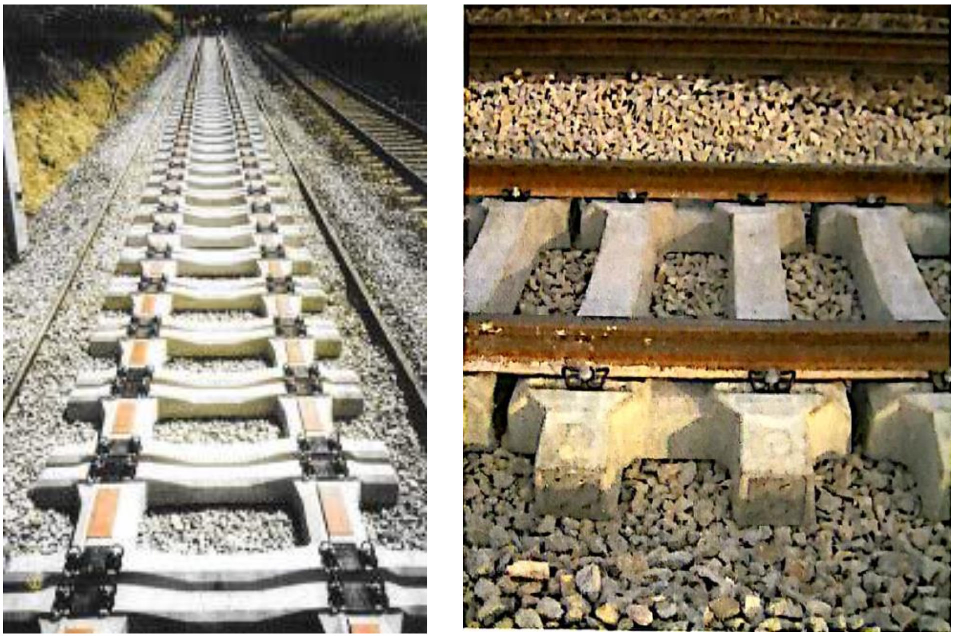
The features of conventional ballasted track for high-speed lines are [5]:

- UIC60 class rail
- B70W type sleeper with a 60 cm spacing
- Type Zw687a stiff rail pad with an elastic coefficient c= 500 kN/mm or highly elastic Zw900 with c=60-70 kN/mm in case of bad settlement behavior
- 30 cm ballast bed depth
- Highly compacted formation protective layer and frost protective layer

5.1.1. Further Development for Ballasted Track

In the conventional track, vertical loads transmit directly to the sleeper and the areas between sleepers stay unloaded. To equalize these vertical loads on the ballast bed, horizontal tensions are needed.

5.1.1.1. Frame Sleeper



Picture 14 - Frame Sleeper

Frame sleeper is a promising solution to compromise between ballasted track and slab track. It has a longer life and provide a better longitudinal support for rails. Formation of the sleepers is H shape prestressed concrete frames which increase load transmitting. In-situ tests show that frame sleeper has higher resistance in lateral direction and lower settlement values. Experiments also prove that ballast pressure is reduced by 50% using this structure. However; construction cost is higher, and it requires different maintenance technology [47].

One sleeper has two sets of rails fastening, which creates a very high stiffness in the horizontal plane. Longitudinal concrete beams provide a quasi-continuous rail support. This helps to a reduction in settlements of two-third compared to a normal sleeper. Reduced settlements offer higher stability of the alignment and thus a higher availability of the track [3].

5.1.1.2. Ladder Sleeper

The ladder track consists of two longitudinal pre-stressed concrete beams connected by tubular steels to maintain track gauge. Ladder tracks offer reduced maintenance and good drainage. This configuration results in an ultra-light-weight sleeper that is roughly the same weight per track length as conventional track. Ladder track type was common on the early British railways. In the mid-20th century, two types of ladder track were developed by the Railway Technical Research Institute of Japan: ballasted and floating un-ballasted [7].

Picture 15 - Example of ladder track

The ladder track usually results in lower pressures on the roadbed, with both the pressure maximum and the amplitude of pressure pulse lower than the conventional track. The addition of the longitudinal support and rigidity in the ladder track is also beneficial, from increasing resistance to ballast against washout and other forms of ballast degradation. The same structural rigidity also increases resistance to buckling [48]

5.1.1.3. Wide Sleeper

Wide sleepers are 2,4m long and 57cm wide. Their supporting surface is theoretically 80% percentage larger than B70 concrete sleeper and the average surface pressure of 2 kg/cm^2 compared to approximately 3.7 kg/cm^2 in the case of traditional sleepers [3] [5].

After the trials in Germany with wide sleepers, tracks showed the following properties [3]:

- Higher track stability
- 15% higher sideways stability
- Airborne noise emission increased by 2dB
- Body noise emission reduced
- Deformation behavior is appropriate
- Maintenance needs are less than traditional tracks

[7] Source: https://en.wikipedia.org/wiki/Ladder_track

Although results are very promising, cost of construction is 10 – 15% is higher and it requires specific tamping technologies [3].

5.1.1.4. Soled Sleeper

An elastic layer at the bottom of a railway sleeper is defined as a sleeper sole. This robust elastic pad increases the contact surface of ballast particles, ensures positional stability and simultaneous protection from stone damage. In addition, the ballast will have a longer life[8].

Picture 16 Soled Sleeper

5.2. Advantages & Disadvantages of Ballasted Track

Ballasted track technology has been developing for nearly two hundred years. The experience gained during the life of ballasted track constructions has created a huge knowledge base for engineers and made them well-equipped against ballasted track problems. Recent improvements have made ballasted track more competitive against slab track.

The main advantages of ballasted track compared to slab track are:

- Proven technology
- Low construction cost
- Easy to replace track components
- High maintainability
- Relatively low noise emission
- Provides good drainage
- High elasticity
- Allows small corrections on the track layout

Building a ballasted track is faster than slab track but it requires a large amount of rock. If the quarries are far from the construction site, cost and CO2 emissions will rise due to the transportation of ballast. But it still may be more eco-friendly, because a large amount of concrete is used during the production of slab track and cement production is one of the primary factors of greenhouse gas emission. Additionally, due to axle load limitations, slabs

[8] Source: https://www.trackopedia.info/encyclopedia/railway-system/railway-basics/

cannot be transported in large quantity. Thus, more transport operation has to be carried out, this will result in more carbon dioxide emissions.

Steel production for rail is the main cause of emissions in track construction (about 50% of the total emission). However, when comparing ballast to the slab track, it shows a greater emission than the slab track type due to concrete production. According to UIC study, during the manufacturing, implementation and maintenance period, slab track considerably emits more CO2 than ballasted track does (22.8 t for ballasted track and 31.6 t for slab track eq. CO2 by km and year) [49].

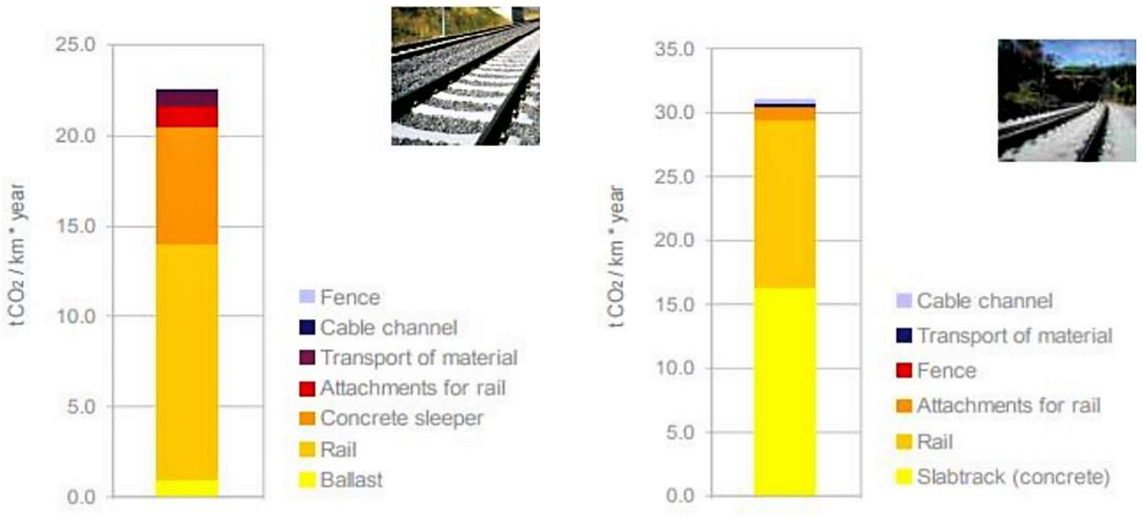


Figure 30 - Carbon footprints of track ballast and slab tracks

The biggest drawback of the ballasted track is the deterioration of the ballast material under heavy traffic load. Ballast degradation can occur because of several factors such as the amplitude and number of load cycles, density of aggregates, track confining pressure, angularity, and most importantly, the fracture strength of individual grains [50].

In the course of time, ballast material is crumbled, turning into finer particles. These fine particles clog the voids between aggregates, therefore, decrease the drainage capacity, volume and porosity. In this situation, the track loses its bearing capacity as well as geometry. Consequently, the ballast needs cleaning or replacement, and track geometry has to be adjusted [3] [5] [6].

The replacement of deformed ballast creates a disposal problem. To minimize disposal cost and externalities due to new quarries, ballast can be washed and re-used in the track. But due to loss of angularity, ballast shear strength reduces, it is expected that recycled ballast produces higher settlement and faster deformation than fresh material [50].

In comparison to slab track, disadvantages of ballasted track are:

- Lateral and longitudinal movement of ballast bed
- Lower speed in curves due to low lateral resistance of the ballast
- Damaging track and rolling stock because of ballast flying phenomenon
- Reduced permeability due to contamination

- Decrease of drainage capacity due to ballast fragmentation
- Requires stronger structures because of heavy material weight

5.3. Advantages & Disadvantages of Slab Track

The ballasted track is economically useful in the short term, but over time this benefit gets less valuable. Although frequent maintenance requirements and speed limitations are the main reasons, slab track has also numerous advantages. However, despite the universal design of the ballasted track, slab track designs vary due to the presence of different manufacturers. Each design has different advantages but mainly they can be listed as below [3] [5] [6] [7] [28] [34]:

- Higher lateral and longitudinal stability
- Rigid track geometry
- Longer service life (50-60 years)
- Maintenance free or less maintenance requirement
- Elimination of churning of ballast particles at higher speeds
- Increased operational capacity (no interruption due to maintenance work)
- Sharper curves with higher super elevation values
- Reduced structure height and weight
- More comfortable and more economical vegetation control
- Eddy current brake can be applied without problem
- Emergency vehicles can drive on the slab track
- Allows steeper route gradients
- Better load distribution
- Excellent riding comfort at high speed

High construction cost is the biggest obstacle to slab track projects and although -theoretically- the system offers a longer service life, there is no running track older than 50 years. These factors have prevented widespread use of slab track so far. However, today the principle of life cycle costing is strongly emerging because studies done in recent years show that slab track can compensate its investment in the long term and even become more economical than the ballasted track.

According to studies of Coenraad Esveld from Delft Technical University, ballasted track with high speed specifications is considerably more expensive than following track types:

- Rheda structure;
- Embedded Rail Structure, not integrated into the concrete substructure;
- Embedded Rail Structure, integrated into the concrete substructure;
- Conventional ballasted track (as a reference).

The result of the life cycle cost analyses conducted by Esveld for the super-structure shows that slab options are more convenient than ballasted track.

Track Type	Construction Cost [EUR/m]	Annual Costs [EUR/m]
Slab track, ERS, NI	1200	90
Slab track, ERS, NI, optimized	860	70
Slab track, ERS, INT	910	80
Rheda	1270	100
Ballasted track	1000	110

Table 10 - Total costs for different types of tracks [51]

Diederich and Schilder found in their study that there is a break-even around year 20 where ballasted track exceeds the accumulated cost of slab track due to the growing maintenance costs.

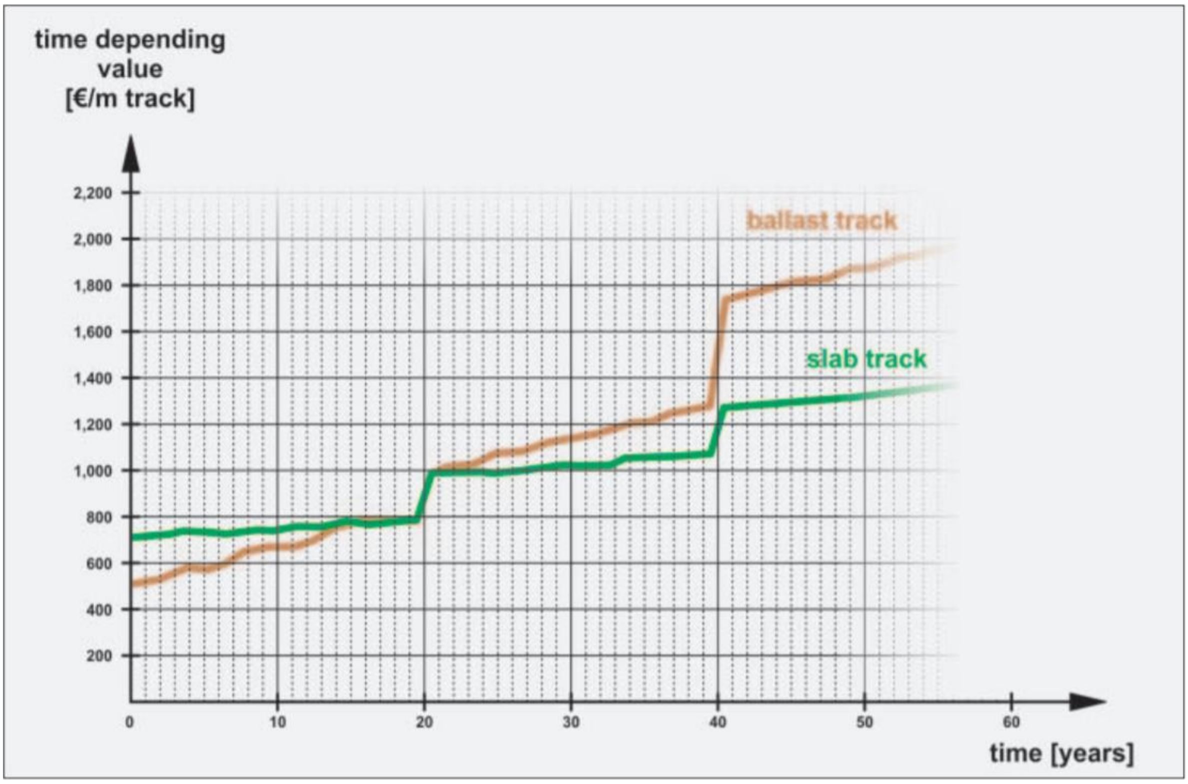


Figure 31 - Development of ballasted and slab track types using discounted cash flow methods

However, most of the studies do not consider soil improvements. The slab track cannot adapt itself to high settlement values nor can be corrected easily as in the case of ballasted track, therefore it requires time consuming and expensive measures during the construction. Decision makers should also consider environmental and social impacts of the alternatives. Externalities such as possible CO_2 emission, noise pollution produced during both construction and service life can play an effective role in decision phase.

Apart from high investment cost, one of the biggest drawbacks of slab track systems is extreme rigidity of its structure. The rigid structure does not allow big transformation such as change in track geometry. Damage caused by an accident or a settlement can be fixed only with a high cost and in a long time. Of course, there are manufacturers who assert the contrary. However, there has been no event to prove or refute these arguments so far.

Other disadvantages of the system are listed below according to the literature:

- Radiate higher noise emission (5dB), extra treatment is needed, which results in higher construction costs.
- The deterioration of the track can occur suddenly and when the system has reached its operational strength.
- The cost of the reconstruction of the slab track is not considered after it has reached the end of its life cycle.
- Transitions between ballasted track and slab track require special attention.
- It requires at least 70 cm thick frost protection layer.
- Expensive repair operations and long-term closures due to the curing and hardening procedures of the concrete (in case of cast-in-place systems).
- Not many possibilities to apply any innovation or future updates after construction
- A defect during the construction would either remain for the entire life cycle or high costly measures should be taken in order to eliminate it.

6. LIFE CYCLE COST ANALYSIS

Life cycle cost analysis (LCC) is a useful methodology for estimating and evaluating the economic performance of a good or service during its lifetime. LCC considers not only investment cost but also all costs associated to the lifetime of the product such as operating costs, maintenance costs, energy costs and its disposal, as well as the social costs generated by its use. LLC typically includes a comparison between alternatives [52].

6.1. Objective of the Work

The objective of the study described in this paper is to set up a LCCA-based method to compare two competing rail track solutions (ballasted and slab). The LCC calculation takes 3 cost categories into consideration: superstructure, maintenance and external costs. User costs have been excluded for this thesis, as these shall not differ considerably in case of different track systems. User costs were deemed to be really uncertain and hard to predict; these have been excluded as well. However, it is discussed in general terms in the following chapters.

Costs considered in the calculations:

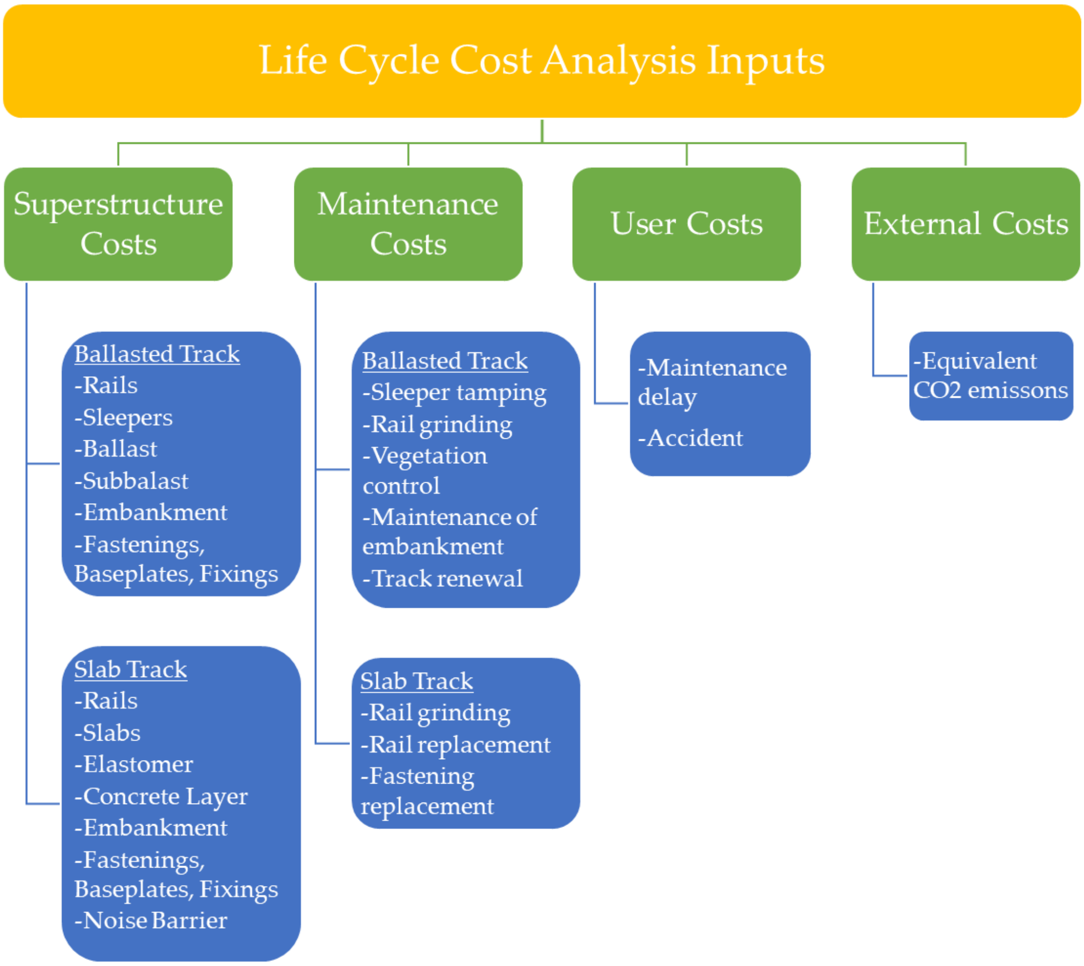


Figure 32 - LCCA Inputs

The LLC model in this thesis was developed by using MS Excel. Inflation rate is considered in the calculations.

$$LCC = \sum_{y=0}^{p} c_y * (1 + r)^y \qquad (1)$$

Where,

- Cy is the cost in year y
- r is inflation rate
- n is the number of years between the base date and the occurrence of the cost
- p is the period of analysis

6.2. General Considerations

6.2.1. Construction Components

6.2.1.1. Ballasted Track

- It is assumed that ballast bed has 0,50 m thickness and 6m width (density: 2800 kg/m3). According to this assumption for 1 km of double track, 8400t of gravel is needed.
- Bituminous sub-ballast layer is used with 200 mm deep.
- Considered rail type is UIC60. It is 60 kg per 1m. For one km double track, 240 t of steel is needed.
- B70 pre-stressed mono-block concrete sleeper is used with space of 60cm. For 1km of double track 3333 pieces are needed.
- Fastenings are elastic fastening type Pandrol Fastclip FC with baseplates and fixings. For one sleeper, 4 sets fastenings are required. 13332 pieces are needed for 1 km.
- It is assumed that the condition of the soil is good and does not require improvement.
- All material has been transported over 100km, 25% by trucks and 75% by rail (diesel).

6.2.1.2. Slab Track

In addition to the above assumptions, at first, the Italian system IPA was chosen for the comparison. However, due to lack of sufficient data, the most similar system, Shinkansen was used instead.

6.2.1.3. Line and Operation Parameters

Since the comparison is made on a hypothetical line, some assumptions must be made before the model setup. These can be modified, or new ones can be added to increase the accuracy of the analysis. These parameters are:

- Demand is assumed to reach 60 MPax per year in the last decade of the project life. It is total demand for both ways. The logarithmic growth rate was applied for certain time periods.

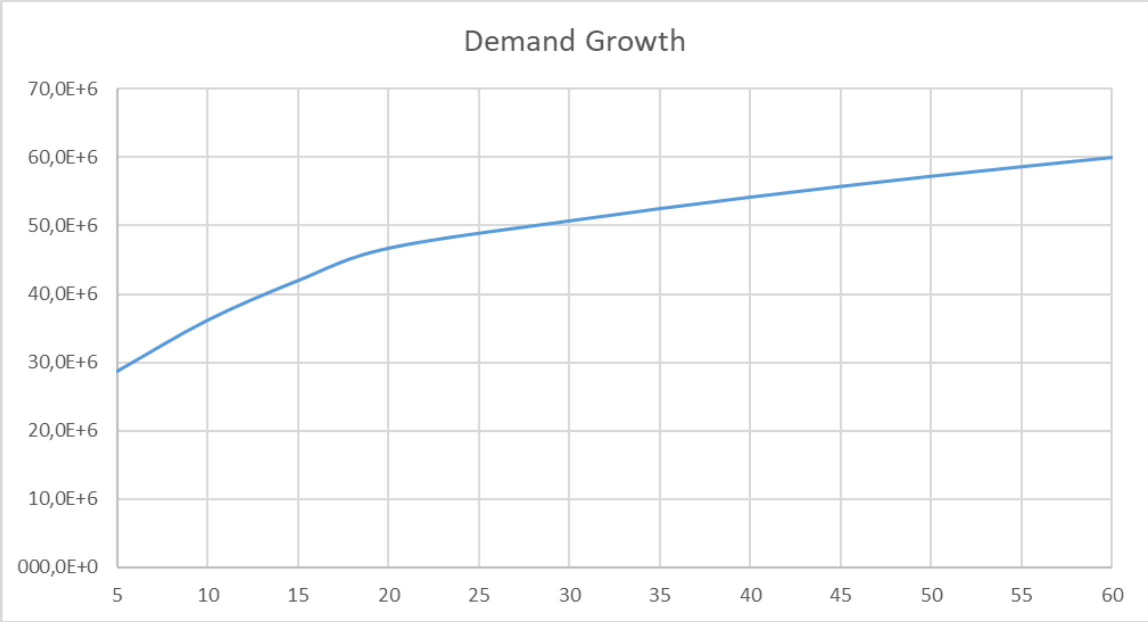


Figure 33 - Development of demand

- Mixed traffic is not allowed, and the features of the selected train set have been given below. The average speed between stations was considered %80 of max speed according to the world speed survey 2007 compiled by Dr. Colin Taylor.

Train Model	Max speed (km/h)	Capacity (q)	Tonnage	Wheelbase (m)
italo AGV ETR 575	300	446	272	3

Table 11 - Features of selected train set [9]

The purpose of choosing this train is to offer high passenger capacity in low tonnages compared to its competitors. This is important, because higher loads contribute more to the track deteriorations.

- The inflation rate (r) is assumed 1,77 %, which is the average of the last 20 years data of Italy according to World Bank [10].
- Operation hours (OH) is selected 18 hours due to maintenance requirements.
- Train occupancy rate (τ) is set to 80%.
- Headway ($t_{headway}$) is considered 3 minutes similar to Shinkansen.
- Dwelling time for embarking and disembarking is considered 1,5 minutes.
- Length of the line is considered 500km.
- One station every 50km and two terminals.

Table 12 below summarizes the parameters chosen for analysis.

[9] Source: https://www.hochgeschwindigkeitszuege.com/zuege.php

[10] Source: https://data.worldbank.org/indicator/FP.CPI.TOTL.ZG?end=2018&locations=IT&most_recent_year_desc=false&start=1989

Demand	60Mpax
Line Length	500km
Maximum Speed	300km/h
Average Speed	80% of max
Number of Stations	9
Number of Terminals	2
OH	18h
τ	80%
$t_{headway}$	3 mins
$t_{dwelling}$	1,5 mins
$t_{turnover}$	30 mins
Inflation rate	1,77%

Table 12 - Line Parameters

6.2.2.Lifespan of the Components

In the previous chapter 3.1.3, theoretical lifespan has been given for each component. However, these durations may vary depending on the load on the system. In order to calculate the loads, number of the trains that run in the line must be known. This can be calculated based on following formula:

$$\sigma = \frac{D(n)/(2*365)}{\tau * q} \quad (2)\ [53]$$

The demand can be satisfied only if $\sigma < \sigma_{max}$. The maximum number of services per day σ_{max} can be calculated:

$$\sigma_{max} = \frac{OH * 60}{t_{headway} + t_{dwelling}} \quad (3)\ [53]$$

Once the number of trains is obtained, the lifetime of track components can be calculated for maintenance and replacements. According to literature; when the cumulated annual traffic tonnage reaches 700MT, rail replacement should be considered. Rail lifetime λ_{rail} is given by:

$$\lambda_{rail} = \frac{700 * 10^6}{365 * \sigma * train\_tonnage} \quad (4)\ [53]$$

And for the ballast lifetime $\lambda_{ballast}$, following formula can be used:

$$\lambda_{ballast} = \left(\frac{374 * 10^2}{train_{tonnage} * \sigma}\right)^{\frac{1}{3}} * \left(\frac{300}{S_{max}} * \frac{wheelbase}{3}\right) \quad (5)\ [53]$$

For ballast tamping, threshold is selected as minimum tonnage that is 40MT according to Lichtberger [11]. Tamping cycle $\lambda_{tamping}$ can be calculated by:

[11] Source: Track Compendium

$$\lambda_{tamping} = \frac{40 * 10^6}{365 * \sigma * train\_tonnage} \quad (6)$$

For rail grinding, threshold is selected 25MT according to Lichtberger [11]. Grinding cycle $\lambda_{grinding}$ can be calculated by:

$$\lambda_{grinding} = \frac{25 * 10^6}{365 * \sigma * train\_tonnage} \quad (7)$$

According to formulas and assumptions results are:

λrail	20 years
λtamping	2 years
λballast	30 years
λgrinding	1 year

Table 13 - Lifetime of track components

For the fastening system and sleepers, expected lifetime is stated around 40 years in many sources. It is assumed that the fasteners for ballasted track is replaced during line renewal.

6.3. Superstructure Costs

According to the definition of UIC, three main costs should be considered when the high-speed railway is constructed: planning and land costs, infrastructure building costs and superstructure costs. In this thesis, to observe the real impact of different track systems on life cycle cost, only track superstructure cost is taken into account. But generally speaking, planning and land costs include feasibility studies, technical design, land acquisition, legal and administrative fees, licenses, permits etc., which can reach up to 10 percent of total infrastructure costs. Infrastructure building costs can vary between 15 to 50 percent depending on the characteristics of topography [54].

System components were defined in section 6.2.1 and Figure 32; the cost of each component was gathered from different sources.

Component	Ballasted Track (€ per km)	Slab Track (€ per km)
Rails [12]	2,40E+05	3,00E+05
Sleepers [13]	1,08E+05	-
Slabs [12]	-	1,65E+05
Ballast [14]	2,31E+05	-
Elastomer [12]	-	3,69E+05
Subballast [12]	1,05E+05	-
Concrete layer [12]	-	5,30E+04
Embankment [12]	1,20E+05	2,00E+05
Fastening System [13]	7,47E+04	7,47E+04
Noise Barrier [15]	-	5,88E+05

Table 14 - Cost of track components

In section 3.2.1.6, noise emission of slab track and its mitigation measures have been discussed. In this analysis, it is assumed that 1/4 of the track passes through the urban areas and requires additional noise mitigation measure for slab track.

6.4. Maintenance Costs

Maintenance costs are the most complex cost component of an asset during its life because the types of maintenance are dependent on many factors such as deterioration rates, maintenance policy, and budget constraint [55]. To maintain track availability with the highest performance, the network manager has to determine a maintenance plan. There are two main maintenance strategies: corrective and preventive. Corrective maintenance is applied when a failure is occurred. It may require long and complicated interventions. Preventive maintenance is applied when a failure is anticipated.

There are also two different approaches for preventive maintenance: periodic maintenance and condition-based maintenance. Periodic maintenance is based on observation of the lifespan of each component of the track. These activities are scheduled according to the expected service life for each track component as a result of empirical formulas. Condition-based maintenance requires continuous monitoring of the system to detect the defects. Preventive maintenance is applied when the quality of a component is below the given threshold [56]. Nowadays, even though condition-based maintenance becomes popular, curative maintenance is still needed to prevent unexpected event caused by undetectable failures.

In this study, maintenance periods are determined by using empirical formulas and statistical data. The periods and costs for each maintenance measure are given in the following Table 15.

---

[12] Source: The Baltic Journal of Road and Bridge Engineering, LCC-Based Appraisal of Ballasted and Slab Tracks: Limits and Potential, Filippo Giammaria Pratico, Marinella Giunta, 2018

[13] Source: Lineamenti di Infrastrutture Ferroviarie, Franco POLICICCHIO

[14] Source: UIC 2003, Alternative Vegetation Control

[15] Source: Railway Noise and Vibration Mechanics, Modelling and Means of Control, David Thompson

Maintenance Type	Maintenance Interval (MGT)	Year	Cost per km (€)
Tamping [16]	40	2	3,74E+03
Grinding [17]	25	1	3,00E+02
Vegetation Control [18]	-	1	1,30E+02
Maintenance of Embankment [18]	-	1	3,90E+02
Rail Replacement	700	15	2,40E+05
Sleeper Replacement [19]	-	30	1,08E+05
Fastening Replacement [19]	-	30	7,47E+04
Ballast cleaning and/or replacement [18]	374	30	3,50E+05

Table 15 - Maintenance costs and intervals

6.5. User Costs

User costs can be classified under two main groups of delays: the first one is routine delays which are occurred during ordinary activities such as crew changes, crossovers, velocity constraints and irregular delays such as maintenance/renewal, accidents, and short-term speed restrictions based on track conditions [57].

The cost of train delay factors can be divided into five main categories: crew, wagons, locomotives, maintenance and fuel, and most of these costs vary with train composition. Delay costs for railroads range from 200 EUR to more than 900 EUR per train-hour [58].

6.6. Externalities

The externality costs refer to environmental impacts produced during the construction and the life cycle of the track. Environmental impacts can be calculated as CO2 equivalent. According to a study conducted by UIC in 2010, during the construction period 22,8 t eCO2 is produced for ballasted double track per km per year. This value is 31,6 t per slab track [49].

Maintenance emissions are calculated by considering three main maintenance activities: rail grinding, tamping and stone blowing. Stone blowing is an optional maintenance activity for ballasted track and acts to extend the service life of the ballast. According to the study of Milford and Allwood, emissions during maintenance activities are given in the below Table 16:

Activity	eCO2 intensity (kg CO2/m)
Tamping	0.153
Rail grinding	1.0

[16] Source: http://publications.lib.chalmers.se/records/fulltext/159318.pdf

[17] Source: https://www.arema.org/files/library/2011_Conference_Proceedings/Effectiveness-High_Speed_Rail_Grinding_on_Metal_Removal_and_Grinding_Productivity.pdf

[18] Source: UIC 2003, Alternative Vegetation Control

[19] Sleepers and fastenings are replaced when track is renewed.

Table 16 - Maintenance emissions [59]

The social cost of greenhouse gas emission is a measure of the economic harm done by those impacts, expressed as the euro value of the total damages done by emitting one ton of carbon dioxide into the atmosphere [20].

Estimating the cost of the emissions is very difficult, because of different assumptions about future emissions, how climate will respond, the impacts this will cause and how the damages will be evaluated. Some emissions already come with a price tag. Under the European Emissions Trading Scheme (EU ETS); electricity producers, energy-intensive industries and commercial airlines are committed to purchasing certificates for their emissions. Currently, an emission allowance for one metric ton of CO2 or an equivalent gas costs around 25 euros [21] [22]. For the study, this value is taken as a reference. Therefore, the costs arising from externalities are:

Construction Emission	eCO2 Intensity(t/km)	Cost per km
Ballasted	114	2,85E+03
Slab	158	3,95E+03
Maintenance Emission		
Tamping	0,153	3,83E+00
Rail Grinding	1	2,50E+01

Table 17 - External costs

[20] Source: https://www.edf.org/true-cost-carbon-pollution

[21] Source: https://www.en-former.com/en/metric-ton-co2-cost/

[22] Source: https://markets.businessinsider.com/commodities/co2-european-emission-allowances

7. RESULTS

The analysis focuses on lifetime superstructure cost of ballasted track and slab track based on construction, maintenance, and social costs. In this way, it is studied that, whether the slab track is also economical for conventional trains. Any structure such as tunnel, bridge, etc. is not specified along the track in order to be able to compare two systems purely and simply.

Several models are developed to highlight the influence of several parameters in the choice of track type. The aim of this is to answer the following questions:

- How does the inflation rate affect the life cycle cost?
- Is the length a factor in the track type selection?
- What is the impact of annual tonnages on costs?
- Which system is environmentally more harmful in terms of CO2 production?

7.1. Base Model

The results of the base model support some previous similar studies performed by scholars. Figure 34 shows the cost development of both systems during their lifetime. The first 5 years is considered as a construction phase, and as it is seen, the investment cost of slab track is quite high compared to the ballasted track (around 200M €). After the line is started to operate, the trajectory of the cost of slab track continues almost horizontally while that of ballasted track increases due to maintenance work. Around its 30th year of the operation, ballasted track requires track renewal while slab track continues its operation with a little preventive maintenance work. After this point, slab track becomes more economical. At the end of the 60-year operation, slab track compensates its investment cost and becomes a more economical solution. During the analysis period, common maintenance is considered to work like rail grinding, rail replacement, etc. requiring equal time interval for both systems. But practically, due to the rigid structure of slab track, system components encounter with lower dynamic loads, thus they deteriorate slower than in the case of ballasted track. Although this information is supported by the literature, there is no clear interpretation about the life of the components since there has been no slab track application for more than 60 years.

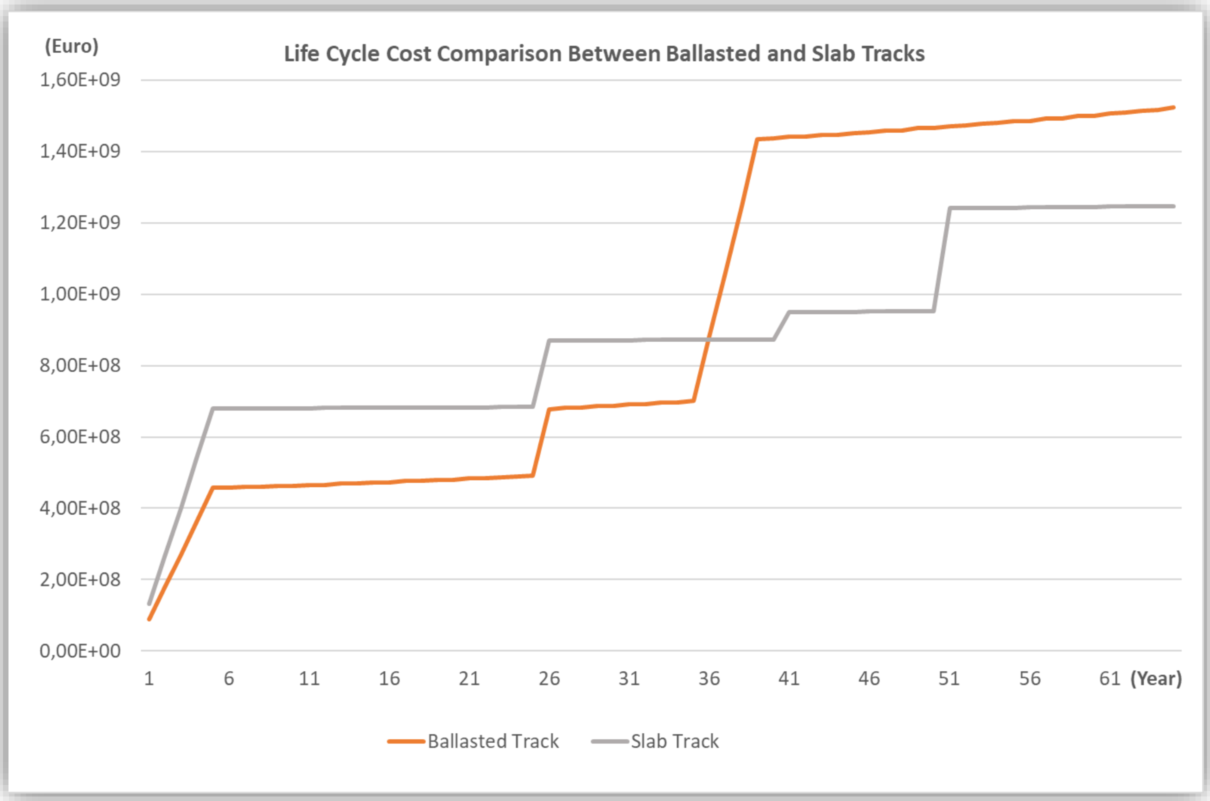


Figure 34 - Life cycle cost development of ballasted and slab track

Figure 35 shows more clearly the total effects of construction and maintenance costs at the end of 60 years.

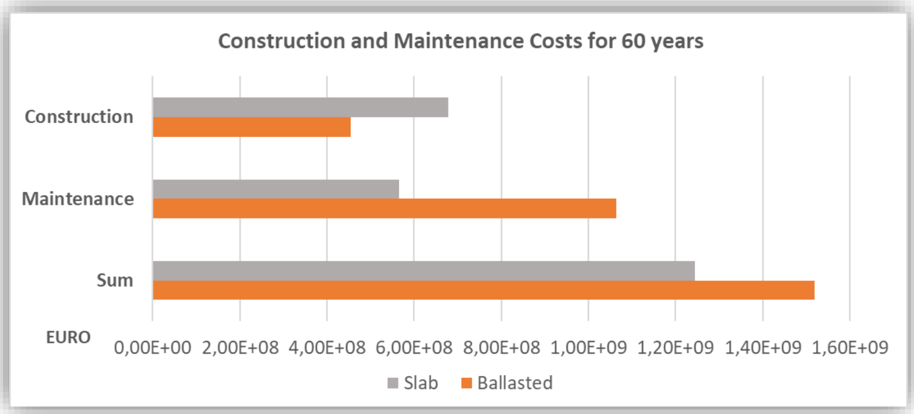


Figure 35 - Comparison based on construction and maintenance costs

During the construction, the slab track produces too much eCO2 due to massive use of cement for concrete slabs. But during the maintenance and renewal works ballasted track, because of the usage of fossil-fueled vehicles cause a higher production of eCO2. Figure 36 shows how the two systems contribute to social cost at the end of 60 years.

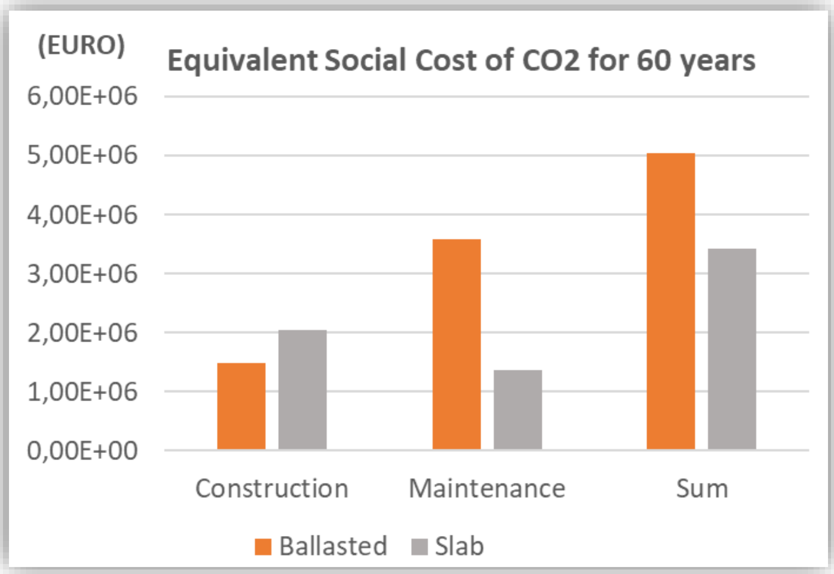


Figure 36 - Social cost induced by eCO2 production

7.2. Sensitivity Analysis

12 different scenarios were applied for two different inflation rates to highlight the influence of selected parameters on the choice of track type.

Variation parameters are as follows:

Length	100, 200,300 and 500km
MGT per year	1,65; 3,29; 9,87 and 19,74
Inflation rate	0 and 1,77%

Table 18 - Model variation parameters

For the 1,65 and 3,29 MGT, empirical formulas give unrealistic high values during the determination of maintenance cycles because of the track components' properties are considered invariants of the study. Therefore, in the scenarios where 1,65 and 3,29 are used, the highest values given in the literature are accepted when determining the service life of the track components.

Inflation rate 1,77%

1) As the line length increases, cost of the slab track starts to catch up the cost of the ballasted track. Because total maintenance cost increases almost linearly for slab track while it increases exponentially for the ballasted track.

2) Annual tonnage is significantly effective on costs in the case of ballasted track. As the tonnage increases, track components and the geometry deteriorate faster. Consequently, their service life decreases. This means track requires more maintenance work. However, slab track cost chances slightly.

3) Although the investment cost for the slab track is higher than the ballasted track in all cases, it is more economical in all lengths and tonnages considering the cost of life.

Above mentioned results can be seen in the following Figure 37and Figure 38.

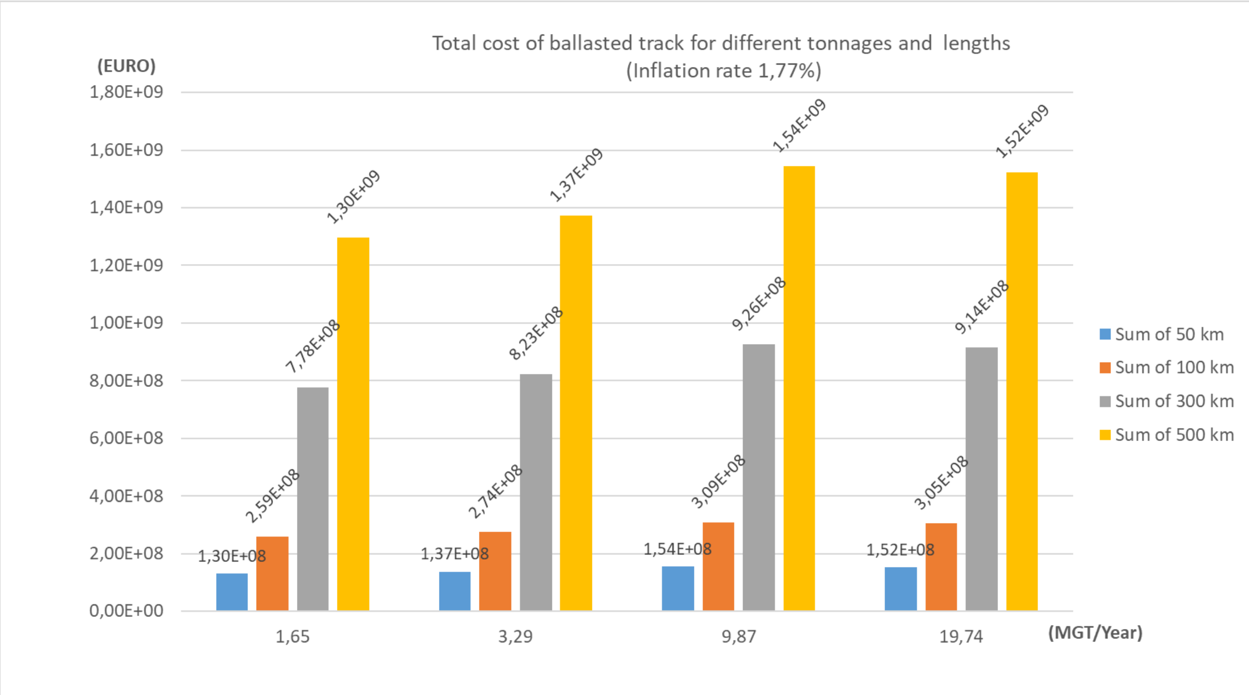


Figure 37 - LCC of ballasted track for different length and tonnage when inflation rate is 1,77

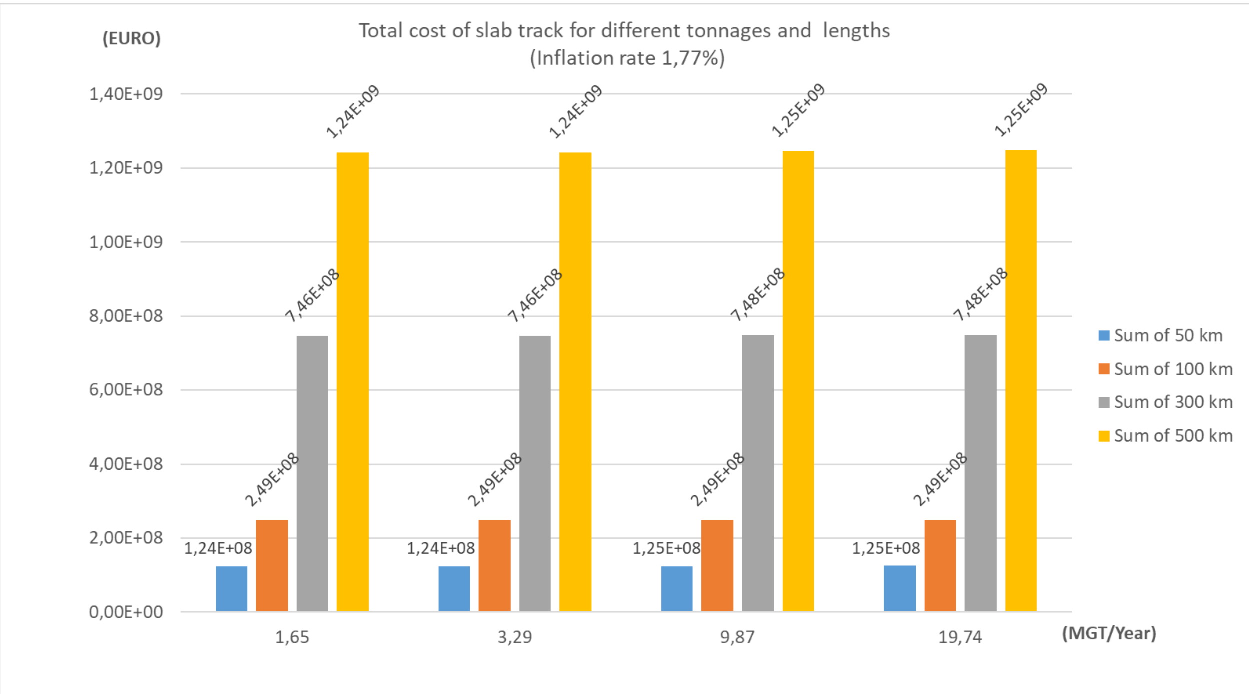


Figure 38 - LCC of slab track for different length and tonnage when inflation rate is 1,77

Inflation rate 0

In addition to the first two results in the case of infection rate 1.77%, as it can be inferred from the following figures, slab track starts to become more economical around after 9 MGT when there is no inflation.

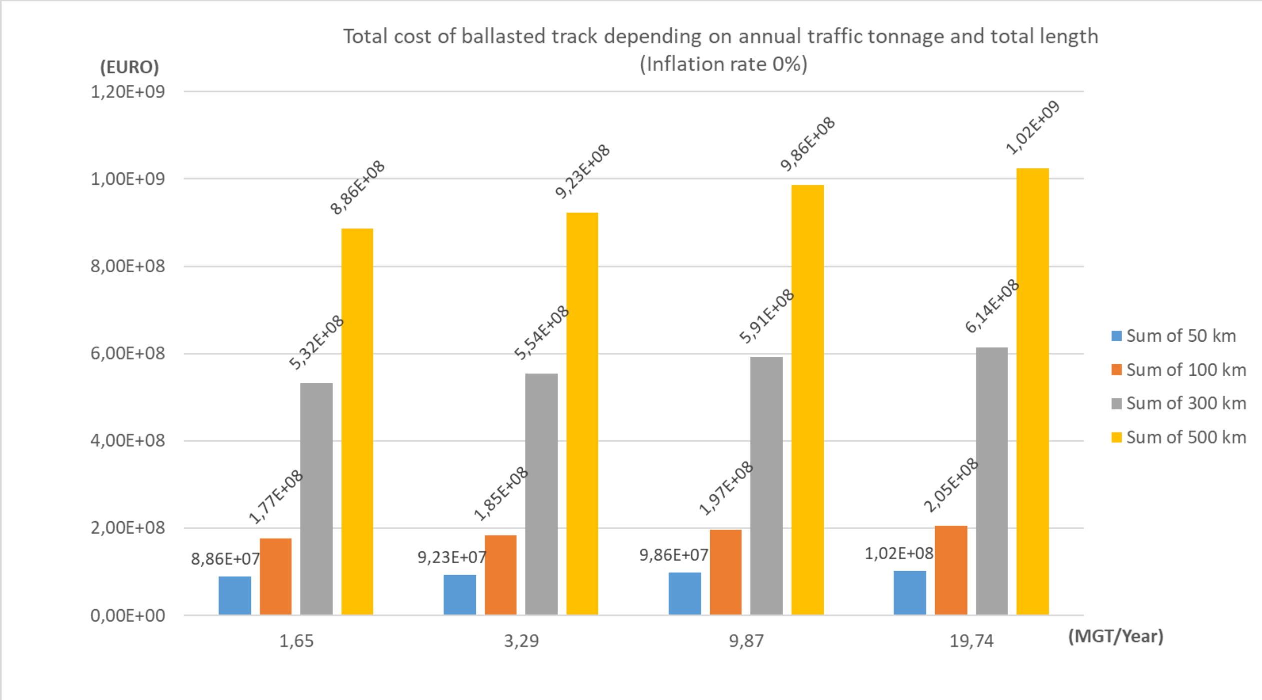


Figure 39 - LCC of ballasted track for different length and tonnage when inflation rate is 0

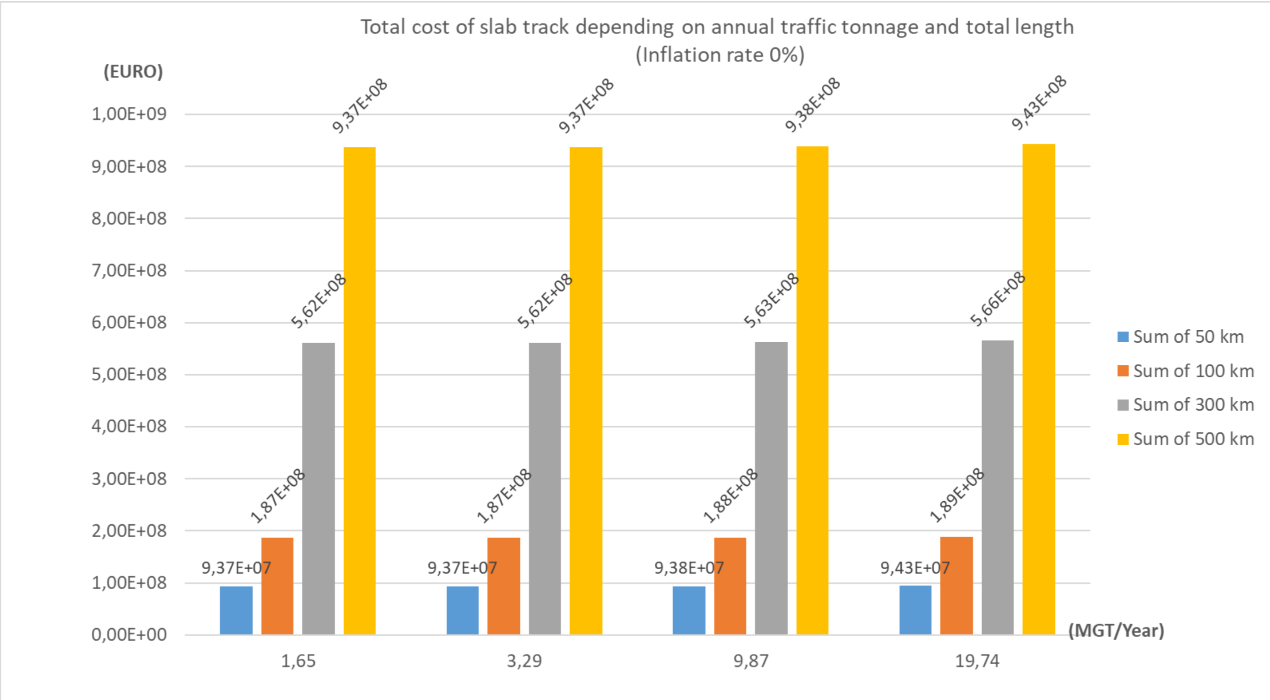


Figure 40 - LCC of slab track for different length and tonnage when inflation rate is 0

8. CONCLUSION

Different slab track and ballasted systems are introduced in this thesis. Detailed descriptions on structures, dimensions, lifespan and maintenance are given for each system. Furthermore, the environmental impacts of railways are briefly mentioned. In the light of these sets of information, advantages and disadvantages of both systems are discussed.

The ballasted track is a proven technology that has developed over the centuries. However, the performance limits of the ballasted track become obvious at high speeds. The increase of speed causes faster deterioration in the track, thus a more frequent maintenance work is required. In addition to this, after a certain speed, under the influence of aerodynamic forces, the ballast material levitates and hurtles around. This phenomenon limits the operating velocity of high-speed trains on ballasted tracks.

Slab track is an expensive solution for above mentioned problems. However, the literature and analysis performed in this study show that slab track compensates its investment cost during its lifetime and becomes even more economical in a long period. Nevertheless, in the slab track systems, service is not interrupted due to maintenance and renewal works as in the case of ballasted track. Consequently, the system makes more revenue.

One of the biggest concerns about the slab track is its repairability. So far, there has been no major accident in a system using slab track. However, academicians indicate that in case of a major accident, such as derailment, repairing processes can be long and costly. This argument may be true in the case of cast-in-place applications. But precast systems such as Shinkansen and OBB-Porr can overcome this problem. Another significant disadvantage of slab track is high noise emission. This problem can be prevented by using noise barriers. Even though this measure increases the investment cost, it does not exceed 3% of the total project cost.

As well as the economic dimensions of the systems, their environmental impacts should be considered before implementation. In this study, environmental impacts are evaluated based on eCO2 emissions. Slab track causes eCO2 production noticeably higher than ballasted track. But analysis shows that due to fossil-fueled vehicles usage during maintenance and renewal works of ballasted track, the total amount of eCO2 is higher in long periods.

In the LCC analysis, only the superstructure costs are focused on. As a result of the study, it can be inferred that slab track is more advantageous in high tonnages. This can be interpreted as follows: The slab track does not only have to be used on high-speed lines. At the same time, it can also offer a convenient solution for low-speed tracks with high tonnage.

In conclusion, slab track should not be considered only when the high speed is the case. In the long term, it is more economical, safer and more environment friendly.

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