Modern Railways for Cargo and Passenger Traffic
High Speed- Heavy Loads
Track Systems

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ABSTRACT: The paper discusses the major components of railway superstructure systems, their dimensioning, and their role in guaranteeing a safe and efficient transportation of passengers and goods.

KEY WORDS: Railway superstructure, heavy loads, high speed

1 INTRODUCTION

Over a period of nearly 200 years the railway superstructure has been continuously improved both with respect to the train speed and its bearing capacity. In 1825 the speed of rail transport was about 20 km/h. Nowadays passenger trains run at speeds of 300 km/h and higher. Similar progress has been made with respect to the axle load, which has been steadily increased from about 2 tons in 1825 to 22.5 tons in 2005.

This increase in speed and bearing capacity has been made possible by the technological advances in railway superstructure design and construction. Meanwhile the exploration of the two frontiers “higher speed” and “heavier loads” continues, and modern track systems are being developed in order to meet the demands of the future.

2 RAILWAY TRACK SYSTEMS

There are two major types of railway track systems currently in use: ballast track and slab track. Both systems are divided in a superstructure and a substructure part. In the case of a ballast track, the superstructure consists of the rails, the rail fastening system, sleepers, and the ballast bed. Everything below the ballast layer belongs to the substructure. In the case of a slab track system, the ballast is replaced by a concrete or asphalt slab and a hydraulically- bonded layer. For both kinds of tracks systems, the substructure is formed by a non- bonded frost protection layer and a foundation layer.

The purpose of the railway superstructure is to supply guiding and load support for the rail vehicles. The rails serve as guiding and load support devices. Load transfer is achieved by a system of elastic layers whose stiffness decreases from top to bottom. This guarantees that the wheel load of typically Q=100 kN is distributed over increasingly larger areas, thereby effectively reducing the stresses σ acting on the railway structure in each consecutive layer. This is illustrated for a ballast track in Fig. 1.

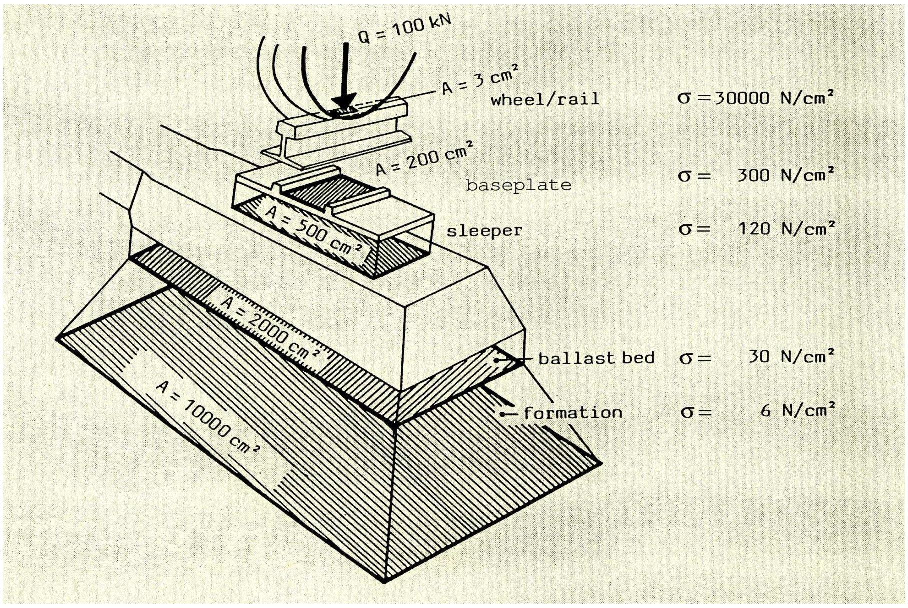

Figure 1: Principle of load transfer (Esveld, 1989).

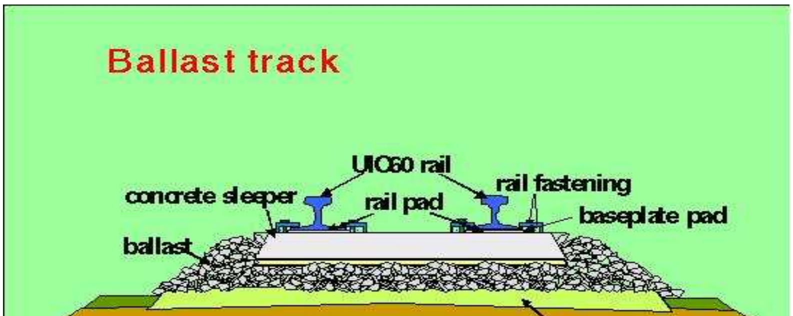

Figure 2: Construction elements of a ballast track.

Figure 2 shows the standard construction elements of a ballast track. The rail fastening, rail pad, and baseplate pad provide the elastic links between the rails and the sleepers. These components transfer the static loads and damp the vertical, horizontal, and longitudinal dynamical loads due to the wheel-rail interaction. Sleepers transfer the static axle load to the ballast and provide sufficient lateral track stiffness so that a constant track gauge width is maintained. Further load distribution is provided by the ballast bed. It also serves as a drainage system for the surface water, which must necessarily be drained off as close as possible to the surface. Typically, two substructure layers, namely a frost protection layer (which depends on the climate) and a foundation layer are needed to guarantee sufficient bearing capacity of the entire track structure. Ocassionally, it is necessary to include an additional sub-ballast or subgrade layer in order to protect the superstructure from ascending sand and soil. If the necessary elasticity cannot be achieved with these standard superstructure elements, it is possible to implement sleepers with elastic sleeper footings and/or elastic sub-ballast mats (see sect. 3.1).

For the dimensioning of a track system with a required bearing capacity, a standard calculational method exists. This method as well as some further developments thereof at my department will be briefly described in the following.

2.1 Static loads

The Winkler model is the standard model used in track design. In the Winkler model, half of the track is idealized as a Bernoulli beam (rail) on an elastic foundation (sleepers, ballast, substructure). This is depicted in Fig. 3. The basic model assumption is that the stress σ under the wheel load Q at the location x is proportional to the local rail displacement $z(x)$. The constant of proportionality is called the *modulus of subgrade reaction* C. It describes the elastic reaction of the sleepers, ballast bed, and railway substructure to the vertical load in terms of a continuum of identical vertical springs.

There exist several methods for calculating the elastic foundation constant C. They are based on the idea that the elastic behavior of a layered system can be approximated by a single layer, which has the same elastic modulus as the softest layer and a thickness given by the elastic moduli and heights of the individual layers. The calculational details for converting a multi-layer system into a single layer system can be found e.g. in Eisenmann and Mattner, 1991. Typical values for C are in the range 20 N/cm³ (sand) - 100 N/cm³ (rock).

This model allows to calculate the resulting rail bending curve $z(x)$, where z is the vertical displacement under the wheel load Q. This curve is characterized by the maximum deflection z_0 and the elastic length L, which describe, respectively, the magnitude and range of force acting on the railway track structure (see Fig.3). Both parameters are given in terms of the elastic modulus E and moment of inertia of the rail, the width of the beam b, and the modulus of subgrade reaction C

$$z_0 = \frac{Q}{2bCL} \qquad\qquad L = \sqrt[4]{\frac{4EI}{bC}} \qquad (1)$$

The maximum vertical rail deflection z_0 and the elastic length L are important parameters in track dimensioning. For a given wheel load Q and rail parameters E and I, a stiff railway construction (large modulus of subgrade reaction) implies a small z_0 and elastic length L, whereas a soft track construction (small modulus of subgrade reaction) leads to a larger vertical rail deflection and elastic length. In the latter case the load is distributed over a wider range, which in turn leads to a reduction of track wear. On the other hand, a larger z_0 also leads to an increased driving resistance because the wheel is (figuratively speaking) permanently moving up a steeper hill provided by the bending curve. Therefore, an optimum between load distribution and driving resistance has to be found.

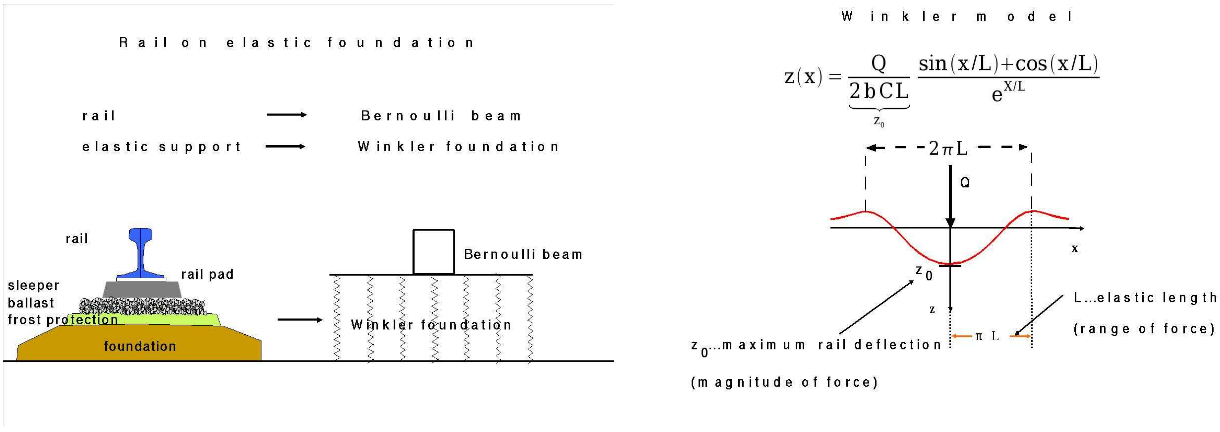

Figure 3: Left: Description of the rail and the multi- layered railway structure as a Bernoulli beam on a Winkler foundation.
Right: Rail bending curve $z(x)$ under a static load Q as calculated in the Winkler model.

The elastic layers of railway track systems are dimensioned in such a way that the maximum vertical deflection under a static wheel load of Q=100 kN is about z_0=1.5 mm. This guarantees that wear and track deterioration is minimized while travelling comfort in passenger trains remains at a high level.

It is possible to apply the Winkler model of a continuously elastically supported longitudinal Bernoulli beam to a ballast track with transverse sleepers. To this end, the load support area provided by transverse sleepers located at regular distances along the track is converted into an identical area of an equivalent longitudinal beam of width b.

We have applied the Winkler model also to horizontal rail bending. This topic has not received much attention in the past, despite the fact that horizontal forces can be large. Horizontal forces may have a major influence on the lifetime of the track system and play an important role in the problem of vibration and noise emission from railway lines (Hohnecker, 2001). The latter issue will be discussed in more detail in sect. 4.

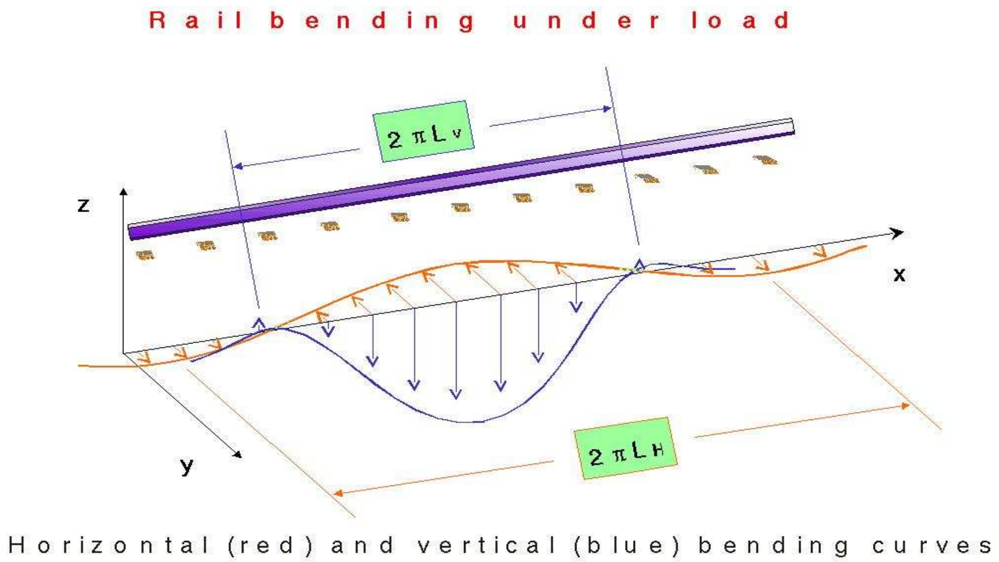

Figure 4: Horizonal and vertical bending curves with their characteristic elastic lengths L_H and L_V.

We have also used the two-parameter Pasternak model (Selvadurai, 1979) to calculate the rail bending curves. The Pasternak model includes in addition to the compression layer, described by the modulus of subgrade reaction *C*, a shear layer with shear modulus *G*. This allows the elastic foundation to deform under shear stress, and provides a more realistic description of the railway track. The additional shear layer can be pictured as supplying a horizontal coupling of the vertical Winkler springs (see Fig. 5). Due to the shear layer, the elastic length is increased and the maximum deflection decreased compared to the one-parameter Winkler model.

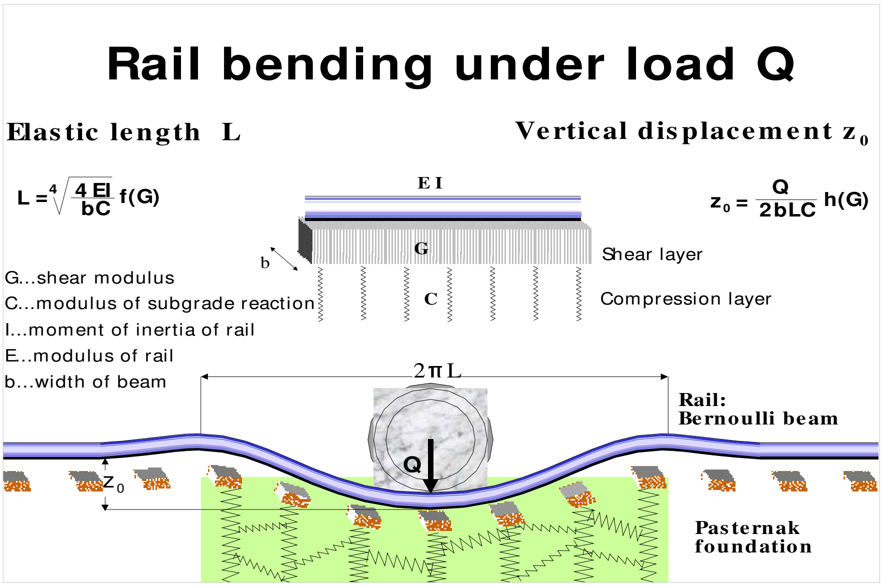

Figure 5: Pasternak model.

2.2 Dynamical loads

When a train is moving, the presence of curves, gradients, and track imperfections inevitably leads to additional forces ΔQ both in vertical and horizontal directions. Fig. 6 shows the results of measurements of vertical dynamical wheel loads Q [kN] for two locomotives as a function of the train velocity v [km/h]. It is evident that for higher train speeds the dynamical wheel loads can be as large as 50% of the static vertical wheel load or even larger if the train velocity exceeds 200 km/h.

The railway superstructure must be dimensioned in order to absorb these additional forces. In practice this is done by adding velocity dependent safety margins to the dimensions calculated for static wheel loads. With increasing vertical dynamical loads the horizontal forces also increase. This puts higher demands on the lateral stiffness of the track. Recent developments aim at upgrading the ballast track for higher speeds and train loads. They have led to innovative sleeper designs, e. g. broad frame sleepers. This will be briefly discussed in sect. 3.

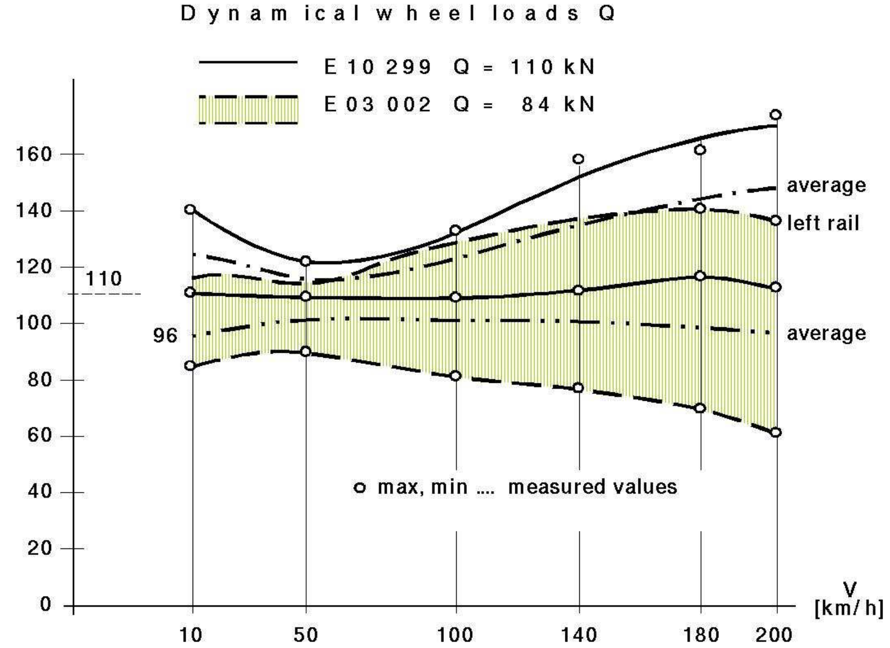

Figure 6: Measured dynamical wheel loads (Birmann, 1967).

In summary, the bearing capacity of a railway structure depends on the stiffness and thickness of the individual elastic layers. For a desired static wheel load and train velocity the dimensioning of the track is done with the help of the Winkler model. In this context, it is important to note that different countries use different standard axle loads for track dimensioning. In Germany, the standard axle load is 225 kN, whereas the British rail uses 250 kN. There is a tendency to push for axle loads of 250 kN in Germany. The Ofotbane in Norway is designed for an axle load of 300 kN (see Fig.7). In the United States and Australia, heavy haul trains require railway structures which can support static axle loads of 350 kN.

Figure 7: A 14-axle locomotive on the Ofotbane between Kiruna and Narvik.

2.3 Bearing capacity classification

A simplified method for dimensioning railway structures was developed by the UIC. The bearing capacity of a railway structure depends on the bearing capacity of the substructure. According to the UIC code 719R, the latter is divided into three classes

- P1 bad
- P2 average
- P3 good

A similar UIC classification exists for the bearing capacity of the natural foundation (soil)

- QS0 insufficient (e.g. clay)
- QS1 bad (e.g. weathered slate)
- QS2 average
- QS3 good (e.g. granite)

Depedening on the quality of the natural foundation, additional layers must be introduced and the thicknesses of the various substructure and superstructure layers must be increased in order to achieve the desired bearing capacity and speed of the railway line. The details of the simplified calculational scheme can be found in UIC code 719 R, 1994.

Railway lines are distinguished according to their load bearing capacity according to the UIC categories (UIC code 700 V, 1987) shown in Table 1.

Table 1: Railway line categories according to their load bearing capacity.

category	axle load [kN]	vehicle weight/m [kN/m]
A	160	48
B1	180	50
B2	180	64
C2	200	64
C3	200	72
C4	200	80
D2	225	64
D3	225	72
D4	225	80

Further details can be found in Esveld, 2001.

3 MODERN RAILWAY TRACK SYSTEMS

3.1 Ballast track

The elements of a ballast track have already been described in sect. 2. The main advantages of a ballast track is that its elements are easily accessible and replaceable. Nowadays, the standard ballast track system in Germany consists of B70 sleepers and UIC 60 rails. It can be used for axle loads of 225 kN and train velocities up to 200 km/h.

The weakest element of a ballast track is the ballast. Due to the sharp edges of the ballast stones, the effective sleeper-ballast contact area is only about 10% of the geometric load support area of the sleepers (Riessberger, 2000). This concentration of the load to individual sleeper-ballast contact points results locally in very high pressures and leads to a gradual destruction of the ballast particles. To upgrade a ballast track for higher speeds and axle loads of 250 kN, innovative sleeper designs, such as broad frame sleepers have been developed (Riessberger, 2000). These frame sleepers increase the effective load support area and the lateral stiffness of the track.

Another measure to upgrade a ballast track are elastic sleeper footings and/or sub-ballast mats. The inclusion of these elastic element makes the entire track softer (smaller C) and leads to a better load distribution. Sub-ballast mats also protect the ballast bed from becoming contaminated with fine-grained materials, which would reduce its load distribution capacity. The use of rails with broader rail foots in combination with softer baseplate pads (Stahl 1999) has also been proposed. However, there are limits beyond which ballast track would require very high levels of maintenance at relatively short time intervals. This becomes apparent at high train velocities.

3.2 Slab track systems

At higher train speed v > 200 km/h the wheel-rail interaction leads to increased vibration emission from the wheel-rail contact zone. These vibrations are also transmitted into the ballast bed, where they cause a high wear of friction. As a result, the ballast bed loses its elasticity. Moreover, at certain vibration frequencies, the ballast behaves like a liquid and flows out from under the sleepers. This leads to a rapid deterioriation of the track quality and make frequent maintenance, in particular, tamping necessary.

In order to achieve higher train velocities and a permanently good track quality, different ballastless track systems have been constructed. In Germany alone more than 40 different slab track systems (Mattner and Freystein 2002) have been authorized during recent decades. Slab tracks are now the standard solution for the construction of new high speed lines in Germany. Their main advantages compared to a ballast track are: (i) better load distribution, (ii) higher lateral track stiffness, (iii) more accurate track geometry, (iv) longer lifetime, (v) lower overall costs. There are two major types of slab track systems, namely those with discrete and those with continuous rail support (see Fig. 8). Among the discretely supported systems one distinguishes between compact solutions, where the sleepers are concrete-casted and nonembedded systems where concrete sleepers are mounted on top of a concrete or asphalt slab.

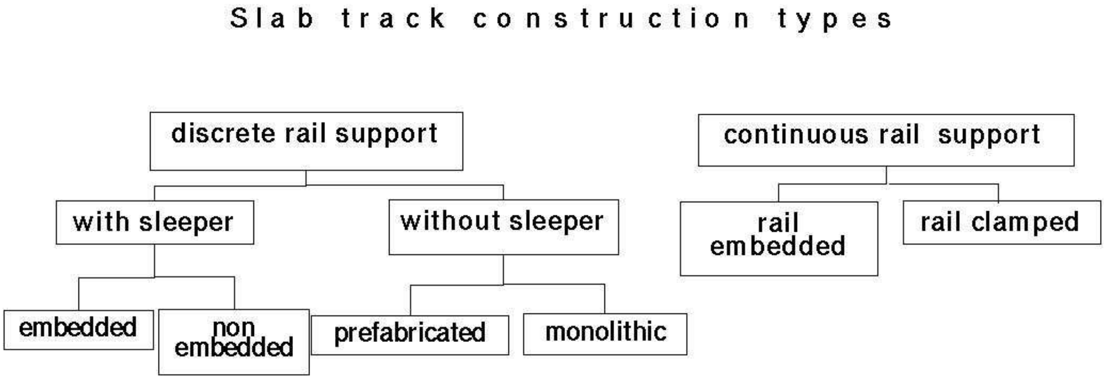

Figure 8: Various slab track construction types.

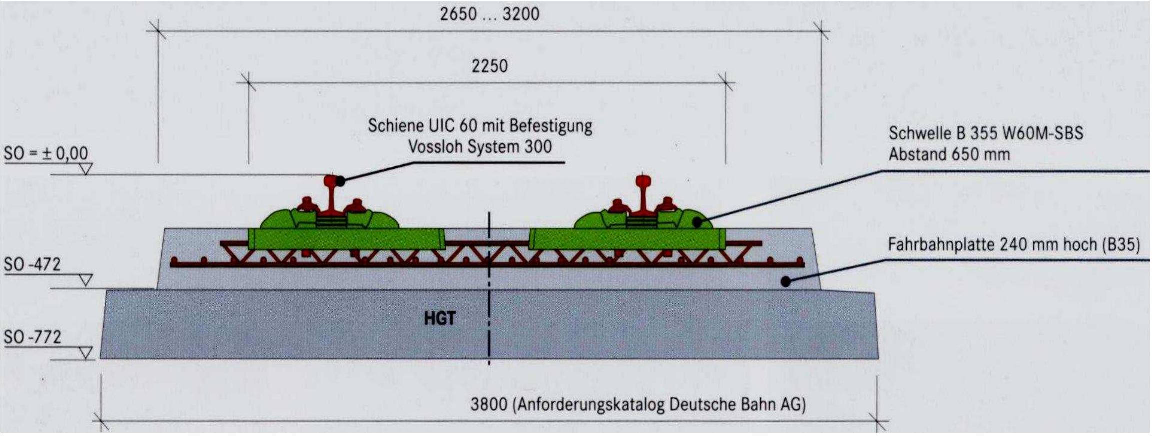

Figure 9: Slab track system Rheda 2000 with discrete rail support.

The system Rheda is currently one of the standard slab track systems in Germany. It belongs to the class of slab track systems with discrete support and embedded sleepers. Since the first Rheda test track was built in 1972, there has been steady progress in improving this system culminating in the Rheda 2000 system shown in Fig. 9.

Another modern slab track development is the embedded rail system (ERS) Infundo. It consists of the following components: (i) rails, which serve as guiding devices and provide load support; corkelast material, which provides continuous elastic rail support, and vibration damping, (iii) elastic pad, which provides the required vertical deflection of the rail, (iv) concrete slab, which provides load support and distribution, as well as track gauge stability.

The Infundo ERS does not employ bolts, nuts, clamps, or any of the usual rail fastening components. Instead the rails are placed in a concrete trough and fixed by a pourable elastomer material (polyurethan with cork granulate), called corkelast. The corkelast surrounds the rail foot, rail web, and the lower part of the rail head. Special adhesives guarantee that rail, corkelast, and concrete form a tight and permanent connection. The complete embedding of the rails in the corkelast material provides *continuous elastic rail support,* both in vertical and horizontal direction. Thus the rails are fixed and elastically supported over their entire length and not only at discrete points as in standard railway superstructures (see Fig. 10)

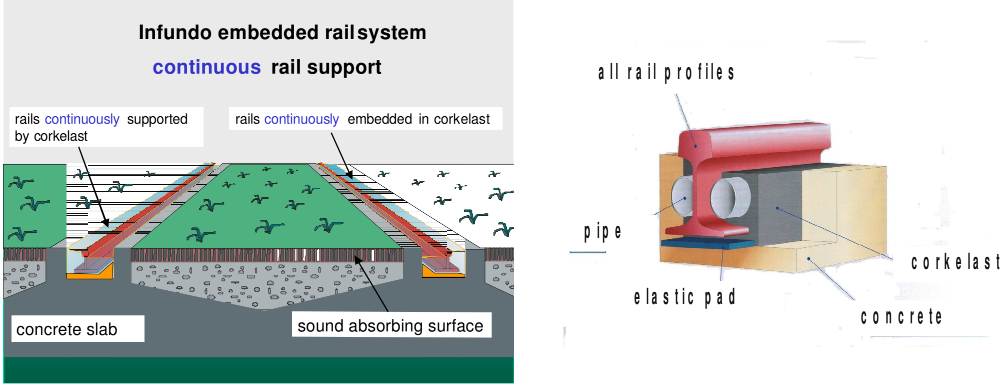

Figure 10: Infundo embedded railway system

4 ENVIRONMENTAL ISSUES

Railways are crucial for a sustained development of modern societies. This has become particularly apparent in recent times. It is widely recognized that the shift of freight traffic from rail to road has been accompanied by adverse effects. Growing pollution and congestion, delays, injuries and death toll are among the negative consequences resulting from this shift in the modal split. There are clearcut environmental advantages of railways compared with other modes of transportation.

A major advantage of railway systems is their economic use of the available land resources. It is well known that the land use of a double track railway system (width 14 m) is considerably lower than a standard four-lane freeway (width 38 m). In terms of passengers per hour and per meter width of traffic lane, cars can move about 200 persons, whereas a train can move 9000 passengers (Smith, 2003).

There is no debate that railways are a very energy efficient way of transporting passengers and goods. The energy consumption per person and km of a passenger train is typically a factor 3 lower than for a car. With respect to freight traffic the energy use per km and ton of a freight train is about a factor of 4 lower than for trucks.

Another environmental issue is the noise and vibration emission from railway lines. Numerous measurements show that slab track systems have higher airborne sound emission levels than standard ballast superstructures. This is partly due to the different sound absorption coefficients of both track surfaces, and partly due to constructive differences (e.g. continuous vs. discrete rail support). Because a ballast track surface has a higher sound absorption coefficient than the concrete surface of a slab track system, one expects lower sound emission levels from the former. As an example, we show in Fig. 11 airborne sound measurements made at the double track test site of the Deutsche Bahn in Waghäusel near Karlsruhe, where an ERS slab track and adjacent ballast track are tested under normal operation conditions.

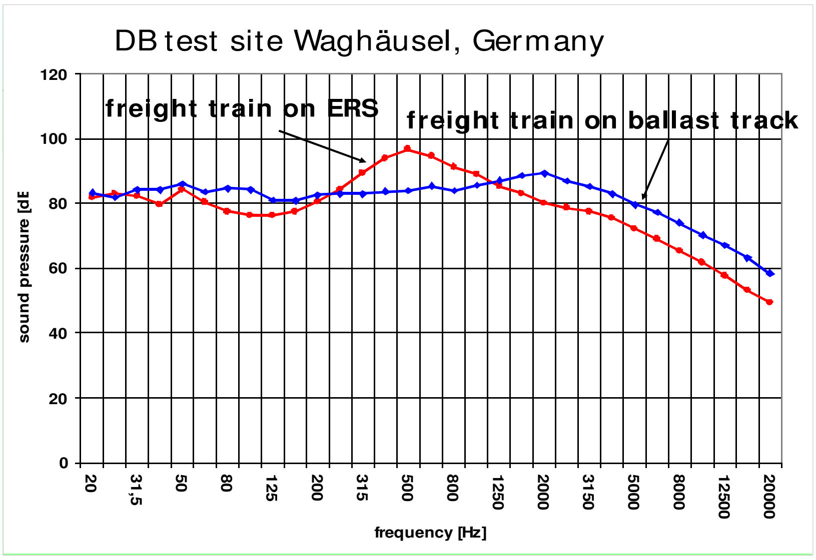

Figure 11: Comparison of airborne sound pressure levels [dB] as a function of frequency [Hz] from Infundo ERS and adjacent ballast track measured at a distance of 5.3 m from the ERS track at the Deutsche Bahn test site in Waghäusel.

One also notices that emission spectra of both types of superstructure are different. The spectrum of the Infundo ERS has a maximum at around 600 Hz where its levels exceeds those of the ballast track by about 10 dB. On the other hand, at higher frequencies above 2000 Hz, where the human ear has its highest sensitivity, the ERS levels are lower than the ballast track by about 7 dB. This reduction at higher frequencies leads to the subjective impression that train passages over an ERS track sound less annoying. However, when summed over all frequency bands, the total airborne sound emission level from an ERS is about 5 dB higher than the corresponding ballast track level. Therefore, further improvements of the acoustic properties of the ERS are necessary. In the case of railbound urban transportation systems, the combination of an ERS with a plant- based track surface reduces the airborne sound levels by about 3 dB and has a positive effect on the urban micro-climate.

5 SUMMARY

In the present paper, I have discussed some features of modern railways.

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