

RECENT DEVELOPMENTS IN HIGH-SPEED TRACK

Coenraad Esveld

*Esveld Consulting Services, The Netherlands
Delft University of Technology, The Netherlands*

Abstract

In this paper some recent developments in high-speed track are highlighted. High-speed networks are expanding rapidly, especially in Europe and Asia. Japan and France were the initiators of high-speed technology. The French network mainly comprises of traditional ballasted track, whereas Japan primarily focused on slab track, with their well-known J-Slab. Studies on life cycle cost and availability have shown that non-ballasted tracks have great advantages. In Europe and other parts of the world, the German Rheda2000 is the leading solution. However these systems could be further optimized, whereby the design cannot be seen separate from the bearing capacity and properties of the subgrade.

In the design the vehicle track interaction plays a dominating role [1]. Short wave and long wave track irregularities should be considered in the dynamic analyses. The maximum geometrical deviations applied in the analyses should also be considered in the track maintenance standards and decision support systems. Special attention is given in this paper to design and maintenance aspects for long wave and short wave track irregularities, including weld geometry.

Keywords: high-speed track, track design, track maintenance, long wave geometry, short wave geometry, slab track, dynamic forces, weld geometry.

1 Introduction

Presently high-speed lines are rapidly expanding, primarily in Asia and Europe. Spain (ADIF) is currently one of the largest investor worldwide with about € 20 billion over 5 years [6]. High-speed technology was originated in Japan and subsequently in France. Later also the Germans followed. The present world record for high-speed originates from 2003 and is hold by Japan with 581 km/h for maglev and by France with 574 km/h for wheel/rail technology. China has now commenced commercial train speeds of 350 km/h. Figure 1 presents an overview of relevant high-speed data.

Country	Total network length [km]	Scheduled trains	Test run speed record	Average speed of fastest scheduled train
Belgium	214	300, 250 km/h	347 km/h	237 km/h
China	6,552	431 km/h (maglev) 350, 330, 300, 200-250 km/h (conventional)	502 km/h (maglev) 394 km/h (conventional)	313 km/h
France	1,700	320, 300, 280, 210 km/h	574 km/h	272 km/h
Germany	1,290	300, 280, 250, 230 km/h (conventional)	550 km/h (maglev) 406 km/h (conventional)	226 km/h
Italy	815	300, 260, 200 km/h	368 km/h	178 km/h
Japan	2,459	300, 275, 260 km/h (conventional)	581 km/h (maglev) 443 km/h (conventional)	256 km/h
Netherlands	100	300, 250, 140/160 km/h	336.2 km/h	<140 km/h
South Korea	240	300, 240 km/h	355 km/h	200 km/h
Spain	1,272	300, 250 km/h	404 km/h	236 km/h
Switzerland	79	250, 200 km/h	280 km/h	<140 km/h
Taiwan	336	300, 240 km/h	315 km/h	245 km/h
Turkey	245	250 km/h	303 km/h	<140 km/h
United Kingdom	109	300 km/h, 225 km/h, 201 km/h	335 km/h	219 km/h

Figure 1 Overview of high-speed lines in the world

Although Japan and France were the initiators of high-speed technology, their track systems are quite different. The French network mainly comprises of traditional ballasted track, whereas Japan primarily focused on slab track, with their well-known J-Slab (Figure 2). Studies on life cycle cost and availability have shown that non-ballasted tracks have great advantages. In Europe and other parts of the world, the German Rheda2000 is the leading solution. However these solutions could further be optimized, whereby the design cannot be seen separate from the bearing capacity and soil properties of the subgrade.

In the design the vehicle track interaction plays a dominating role. Short wave and long wave track irregularities should be considered in the dynamic analyses. The maximum geometrical deviations applied in the analyses should also be considered in the track maintenance standards and decision support systems. Special attention is given in this paper to design and maintenance aspects for long wave and short wave track irregularities.



Figure 2 Ballasted HSL track of KORAIL

Presently all over the world non-ballasted track concepts are being applied, although still at a moderate volume. The main advantages of such structures are:

- Reduction of structure height;
- Lower maintenance requirements and hence higher availability;
- Increased service life;
- High lateral track resistance which allows future speed increases in combination with tilting technology;
- No problems with flying ballast particles at high-speed.



Figure 3 J-Slab (Taiwan HSL)

If the low maintenance characteristics of slab track on open line are to be retained, great care must be taken to ensure that the subgrade layers are homogenous and capable of bearing the loads imposed [2]. The slabs can be precast or poured on site. The most known tracks with precast slabs are the Shinkansen system in Japan, with the so-called J-Slab (Figure 3) and Max Bögl slab track designed in Germany [1, 3]. Examples of tracks with on site poured

slabs are Rheda 2000 (Germany) and various designs of an Embedded Rail Structure [1].



Figure 4 Bögl prefab slab track

2 Slab track structures

If no bending resistance is required, on for instance bridges and tunnels, both precast and on site poured slab track designs can be applied. Problems arise when such structures are built on soils, where some settlements may be expected. In this case there are mainly three ways of applying a slab track [3]:

- Using a slab with reinforcement at the neutral line (e.g. Rheda 2000). Since the bending stiffness of such slab is very poor massive soil improvements are required which makes such slab structure financially less attractive.
- Using a slab with reinforcement at the top and at the bottom of the slab, which improves the bending strength of the track structure. Various studies at TU Delft have shown that relatively high reinforcement percentages of about 1.5 % for a B35 concrete are required [1], [3], [4]. On the other hand only very limited soil improvements are necessary.
- Using bridge or bridge like structures as a substructure in slab track design. The influence of bending of the bridge has a restricted influence on the bending stresses in the track slab.

At places with very soft soils Rheda 2000 on Settlement Free Plate (SFP) is used for HSL-South in The Netherlands (Figure 5). Clear division between sub- and superstructure can be seen from this figure. The substructure consists of SFP's (30 m or 35 m long), supported by piles, while Rheda-2000 forms the superstructure. An important element of the slab track structure is a thin intermediate layer (Geotextile), which is placed between the sub- and superstructures.

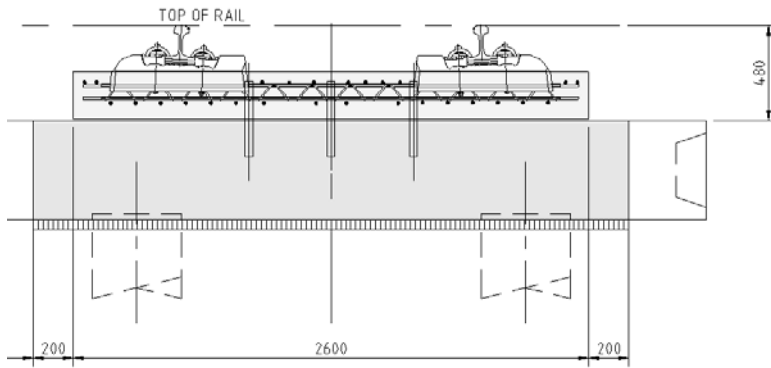


Figure 5 Typical cross section of Rheda 2000 on a Settlement Free Plate (HSL-South)

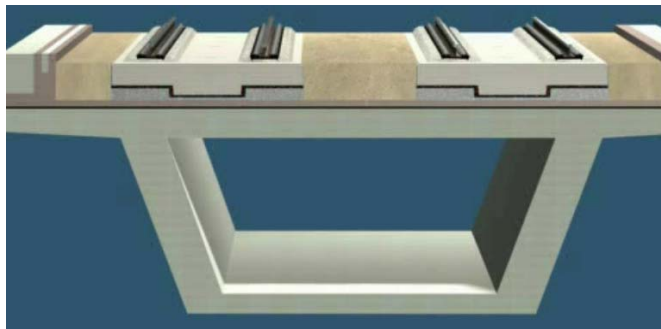


Figure 6 Schematic representation of FFB structure on bridges

In Germany a precast slab track system called Feste Fahrbahn Bögl (FFB), produced by Max Bögl, is in use [2]. This system is to a large extent similar to Shinkansen track. A typical FFB structure consists of transversally pre-stressed precast slabs which are longitudinally coupled using force-transmitting joints, as shown in Figure 4. Such structures can be used on embankments, bridge structures, in tunnels and troughs. One modification of this structure built on a long bridge which is designed for a high-speed line section between Beijing - Tianjin (China) will be discussed in this paper. The FFB (China) structure is almost 116 km long. Approximately 12 km of this structure is built on earth work and approximately 104 km is laid on bridges. Each bridge slab has a length of 31.5 m and consists of the following elements as schematically shown in Figure 6:

- FFB precast slabs
- Grout layer
- Concrete support panel (SP)
- Intermediate layer (Geotextile + Foil)
- Bridge slabs
- Bridge supports

Another example of a pile supported slab track structure is a Neue Feste Fahrbahn (NFF) designed by ThyssenKrupp. A typical NFF track design is shown in Figure 7. The rails are mounted to a precast concrete frame, which consists of two slabs connected to each other. Each slab is mounted to piles by means of three short (transversal) bearers.



Figure 7 Constructional principal of NFF structure

3 Dynamic analysis of slab track

3.1 Analysis procedure

Analysis of the static and dynamic behaviour of a slab track under various loadings is part of the design process, in which both short-term and long-term behaviour should be analyzed. The Railway Engineering Group of Delft University of Technology has developed an approach for assessment of slab track design for high speed lines. The approach is based on the dynamic analysis of a slab track and a number of performance factors calculated on the basis of the results of the dynamic simulations. In the subsequent section the main parts of the assessment procedure are described.

The dynamic analysis of a vehicle-track interaction is performed using the program DARTS_NL developed at TU Delft. In order to reduce the computational effort the modeling is restricted to two dimensions (the vertical and longitudinal directions) and material behaviour is linear. A track structure is represented by a series of alternating hard and soft layers. The hard layers represented by Timoshenko beam elements can be used for modeling track structural components such as rails, sleepers, concrete slabs etc. The elastic interface layers are represented by distributed spring and damper combinations, which can be used to model rail pads, ballast (mats), elastomers etc.

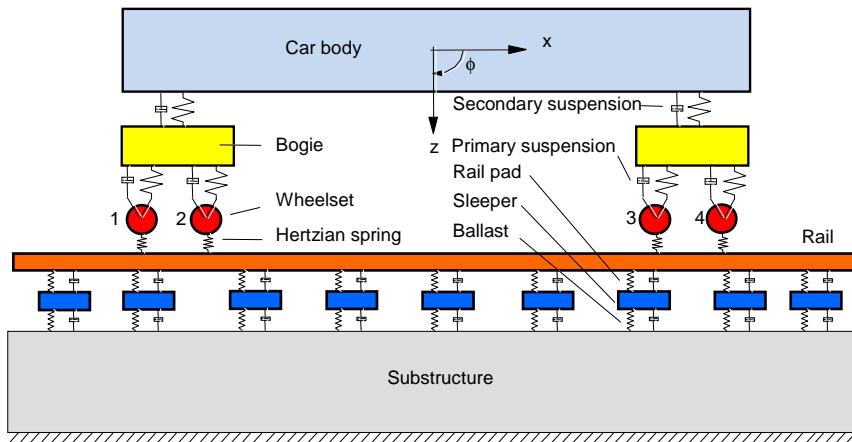


Figure 8 vehicle-track model (a single coach on a classical track) in DARTS_NL

Vehicles are modeled as a mass-spring system. An example of a model for a single car on a ballasted track is displayed in Figure 8. Vertical rail level geometry is an important source of disturbances applied to a vehicle-track system and therefore it should be properly represented in the numerical model. The effect of both short and long wave irregularities must be included in order to obtain realistic results. In DARTS_NL there is a possibility to model the vertical rail level geometry using measurement data. However, recording cars, and in particular the conventional ones, lack long wave information (> 25 m). Therefore, a special vertical rail level geometry profile had to be constructed, combining the measured profile with artificial long wave irregularities. The combined profile has been used in the dynamic simulations of high speed slab track structures (Figure 9 and 10).

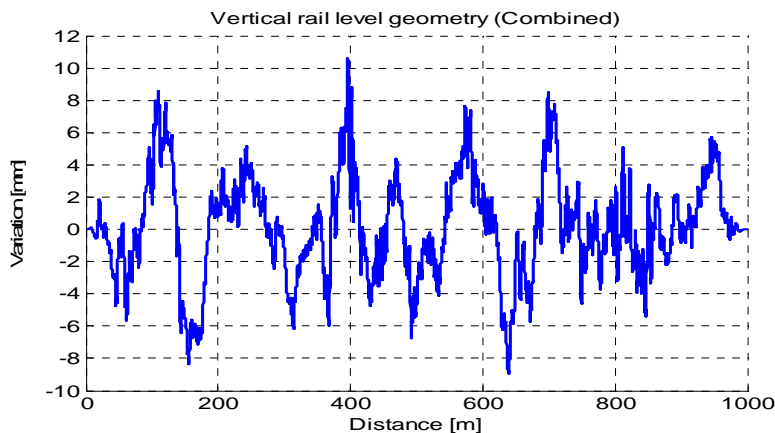


Figure 9 Combined vertical rail level geometry used in dynamic simulations.

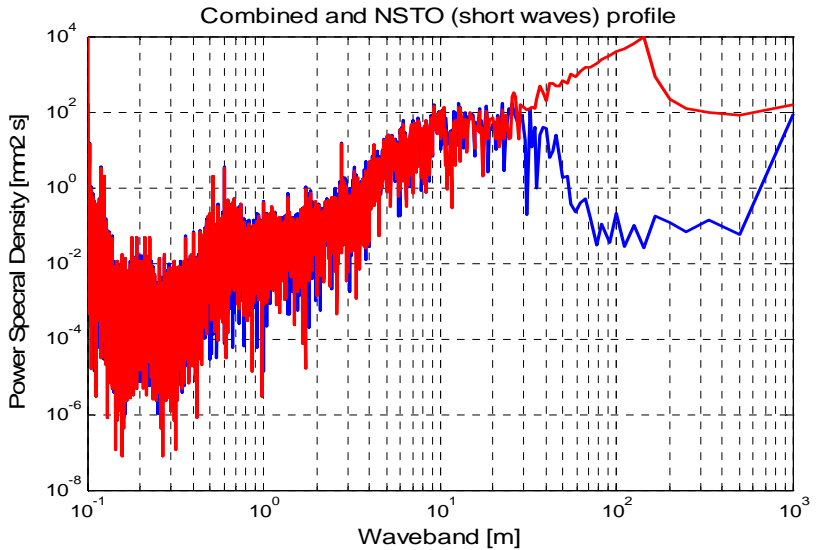


Figure 10 Power Spectral Density of measured (blue line) and combined (red line) vertical rail level geometry profiles.

For analysis of the dynamic behaviour of slab track the most representative part of it (approximately 250m - 300m) has been modeled. The most failure susceptible places in the structure (such as the joints between the concrete slabs and the bridges) should be present in the model. A number of the dynamic simulations for Thalys, ICE3M and (in case of track sharing) ICEMat, travelling with the typical velocities of 90 m/s, 65 m/s and 40 m/s, has been performed.

On top of the previously discussed dynamic analyses results the effects of local dynamic responses due to short wave irregularities, such as poor welds, should be superimposed [5]

3.2 Assessment criteria

In principle, there are three major indicators to assess the performance of a slab track design. Some of these indicators are related to the limit values stated in the Eurocode. The 3 indicators are:

- Car body accelerations: This is an important parameter in the assessment of passenger comfort. Accelerations experienced by passengers should not exceed quality level 2 of the UIC-513 standard. In the DARTS_NL simulations only vertical accelerations are considered, whereas the UIC-513 standards are based on weighted three-dimensional accelerations. With the help of some approximations the UIC standard could be converted to an admissible standard deviation for the vertical car body acceleration of 0.38 m/s^2 ;
- Forces in the interface between wheel and rail: They should be limited to confine the superstructure as well as wheel and rail wear. A simple way

of expressing the dynamic effects is by using the Dynamic Amplification Factor (DAF). As the dynamic force should in fact be considered as a statistical distribution the maximum value has been replaced by its 95% probability, corresponding to two times the standard deviation (2σ). The Eurocode (ENV 1991-3:1995 6.4.3.2) gives a DAF_{95} limit of 1.67 for a 'carefully maintained track' and the limit 2.00 for a 'track with standard maintenance'. The vertical track geometry profiles used in the dynamic simulations had standard deviations of $\sigma = 1.0$ mm and $\sigma = 1.5$ mm, correspond to 'carefully maintained track' and 'track with standard maintenance' respectively;

- Bending moments in the slab structure: They have to be considered with respect to structural strength and fatigue properties. For the slab strength analysis the Dynamic Amplification Factor (DAF) of the bending moments was calculated for both positive and negative moments. The DAF for each group was then determined as the maximum dynamic value over the maximum static value. In case of the Dutch high-speed line DAF values of 1.6 (between piles) and 2.19 (at piles) were achieved.

Based on the analysis of the dynamic results the following conclusions could be made:

- In all simulations Thalys and ICE3M trains have shown an acceptable level of car body accelerations on all considered slab track structures, which does not exceed the required 0.38 m/s^2 ;
- The maximum DAF_{95} values of the wheel-rail contact forces calculated for normal and rough rail geometry were in relatively good agreement with the HSL and Eurocode standards;
- The quality of vertical rail level geometry has a dominant influence on the dynamic responses such as vehicle accelerations and wheel-rail contact forces. For normal rail geometry ($\sigma_{[3-25m]} \approx 1.0$ mm) reasonably good results have been achieved, but higher dynamic amplification can be expected if the rail geometry deteriorates. The results of the simulations have emphasized the importance of maintaining the vertical rail geometry at the required level;
- Influence of the slab track superstructure on the dynamic responses was very restricted, while the influence of the substructure, such as pile spacing and bridge (piled slab) properties, was quite significant;
- Rolling stock parameters especially damping have a substantial effect on the dynamic responses.

3.3 Requirements for maintenance and construction

It is extremely important to carefully control the track geometry of slab track during construction, as corrections afterwards are very difficult. Since a satisfactory level of car body accelerations and wheel rail forces had been achieved in combination with the applied vertical track geometry presented in Figure 11, it is recommended to use this geometry also in the definition of track geometry standards for construction and maintenance.

Waveband	Level	
	Umax [mm]	σ [mm]
3 – 25 m	4.6058	1.0296
25 – 70 m	3.8831	1.3849
70 – 180 m	6.4151	2.7211
0 – 5 m	2.3161	0.30047
0 – 10 m	4.4263	0.70446
0 – 150 m	7.4245	2.5974
Whole profile	10.5941	3.2093

Figure 11 Maximum variation (Umax) and (σ) standard deviation of combined vertical rail level geometry profile

4 Assessment of short-wave irregularities.

Track recording has always played an important role in the quality control of the permanent way. Track recording cars primarily focus on long waves in the track, in the order of wavelengths from 10 – 150 m, which are primarily responsible for the excitation of the car body and thus for passenger comfort. An omission in these systems is that they insufficiently account for the short waves, roughly speaking from 10 m and shorter. These are responsible for the dynamic forces exerted on the track and consequently for track deterioration. From track defect statistics it is well known that track failures and a rapid deterioration of the track geometry are usually caused by poor weld geometry. But also rolling contact fatigue (RCF) defects provide an increasing contribution to these problems.

Already in the 1980s the author has done a lot of research into the influence of weld geometry on the life cycle of track [8]. More recently the development of new theory has got a major boost due to the Ph.D. study of Michael Steenberg [5]. Within this research TU Delft has developed new weld geometry standards for ProRail, the Dutch rail infra manager, based on confining the dynamic wheel rail force, as indicated in Figure 12. The first derivative, or inclination, of the longitudinal rail geometry appears to be the decisive factor. For welds in high-speed operation the norm is 1 mrad, or 1:1000.



Figure 12 Dynamic contact force

A norm without measuring instrument is of course not working. Therefore an electronic straightedge was developed, the so-called RAILPROF [9], displayed in

Figure 13. With this instrument the vertical and horizontal weld geometry are measured simultaneously and analyzed.

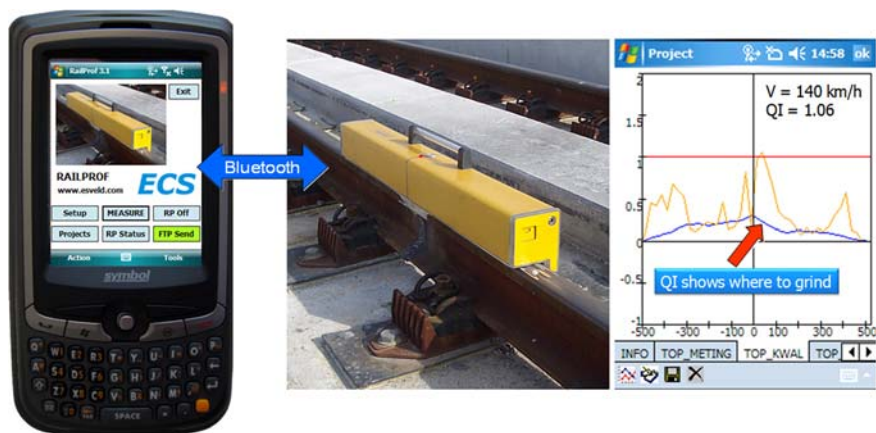


Figure 13 RAILPROF with PDA

The RAILPROF is controlled by a PDA, communicating with the RAILPROF via bluetooth. The PDA is also responsible for storage of the measuring data and assessment of the measurements on the basis of the earlier mentioned first derivative norm. On the PDA screen the welder can immediately see where the weld geometry deviates from the norm and thus where has to be ground. The measuring files can be transferred wirelessly with one click via a built-in ftp client.

5 Best practice in high-speed track design

For a new HSL mostly systems of existing lines are copied, with 'service proven' being the key argument. This approach can be understood, but has a major drawback on technical innovations. The points below are trying to summarize best practice for the design of high-speed tracks, based on experiences with the Taiwan HSL:

- The first thing is of course that the Contractor should comply with the Contract;
- The commissioning body is free to specify which standards and conditions should be applied;
- It is common practice to have a Reference System, either an existing high-speed line, or a system worked out on paper which is also referring to service proven components (for instance fastening systems), or total designs;
- Service proven is most of the times a necessary requirement, but never a sufficient requirement. Service proven means valid under the conditions for that specific line. In a new project often different boundary conditions will be applicable;

- The integral structure should be fully analyzed (detailed design) under the actual dynamic train loads and deformations applied by the supporting structure as specified in the Contract. It is common practice to use Finite Element Models;
- Another argument for a detailed design is that new developments come up quickly and should be used if possible;
- Testing of components like fastening systems is not necessary if certificates are available showing that a component has passed in earlier tests. For all constituents TSI-Infrastructure certificates conform EC Council Directive 96/48/EC have to be present. In addition of course Factory Admission Tests are mandatory. It should be emphasized that 'Service Proven' is by no means a valid argument which could supersede the TSI certificates;
- In general fastening systems have to be tested for each country separately for ballasted track and non-ballasted track;
- In Taiwan basically two high-speed concepts existed, with Shinkansen J-Slab from Japan and BWG turnouts on Rheda 2000 from Germany. Rail fastening standards from Europe (CEN) and Japan (RTRI) are quite different due to a different rolling stock design. It cannot be assumed that a fastening which passes the CEN tests will automatically meet the Japanese requirements and vice versa;
- Short-wave irregularities like weld geometry and corrugation, should be controlled securely in order to minimize detrimental dynamic wheel loads. It is important to do this directly at the installation of a new weld.

6 References

- [1] Esveld, C. (2001) Modern Railway Track. MRT-Productions, Zaltbommel. ISBN 90-800324-3-3 (www.esveld.com)
- [2] Esveld, C. (2003) Recent developments in slab track. European Railway Review, Issue 2, 2003. ISSN 1351 - 1599
- [3] Esveld, C., Markine, V.L. (2003) Developments in High-Speed Track Design. Short paper Proceedings of International Association for Bridge and Structural Engineering (IABSE) Symposium on Structures for High-Speed Railway Transport, Antwerp, Belgium, August 27-29, 2003. pp.14-15 ISBN 3-85748-109-91.
- [4] Markine, V.L., J.M. Zwarthoed, C. Esveld, (2001) Use Of Numerical Optimisation In Railway Slab Track Design. Proceedings of the 3rd ASMO UK / ISSMO conference, Harrogate, North Yorkshire, UK, 9th -10th July 2001. ISBN: 0-85316-219-0.
- [5] Esveld, C., Steenbergen, M.J.M.M.: "Force-Based Assessment of Weld Geometry", Proc. 7th World Congress on Railway Research, Montreal, (2006)
- [6] IRJ, September 2006, page 69-74.
- [7] de Man, A.P.: Dynatrack - a survey of dynamic railway properties and their quality, PhD Thesis, Delft University of Technology, 2002.
- [8] Esveld, C.: STRAIT, Innovative straightening of rail welds, Rail International/Schienen der Welt, July 1983.
- [9] www.esveld.com.