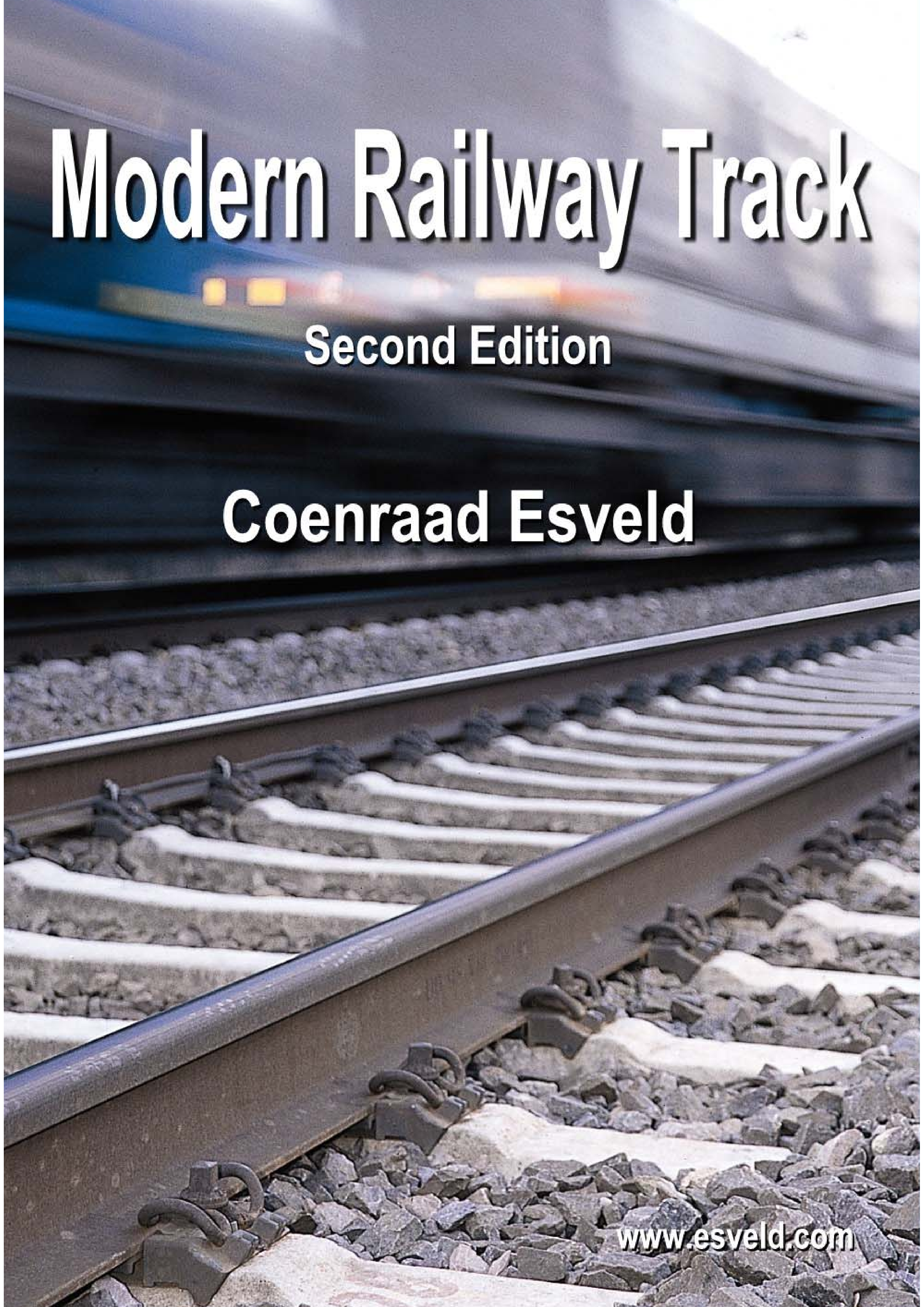
Modern Railway Track

Second Edition

Coenraad Esveld



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MODERN RAILWAY TRACK

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Coenraad Esveld

Professor of Railway Engineering
Delft University of Technology

2001
MRT-Productions

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To my grandchildren
Thomas
Maud
Fieke
and
Douwe

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I would like to conclude with expressing the hope that this Second Edition will once again prove to be a useful contribution to the training of students and railway engineers.

Coenraad Esveld

PREFACE

After the success of Modern Railway Track this Second Edition is an extension and complete revision of the original book, in which the developments of the last ten years have been incorporated. The research projects carried out at the Railway Engineering Group of Delft University of Technology have played a central role. The theory of railway track and vehicle track interaction has been substantially enhanced and much more attention has been given to dynamics. Undoubtedly one of the most important extensions was the part on slab track structures. But also track management systems have been given much more attention. Numerical optimization and testing, as well as acceptance are new chapters.

When revising the lecture notes for the railway course at the Civil Engineering Department of TU Delft in the period 1994 - 2000 the first edition of this book was taken as a starting point. The first edition and the TU Delft lecture notes, together with various publications and research reports, mainly of the railway engineering group of TU Delft, were then forming the base for the second edition.

The staff of the railway engineering group at TU Delft has made a great contribution to the composition and revision of the various chapters. Also the industry provided some important contributions, specifically on the chapters dealing with rail manufacturing, track components, maintenance and renewal, as well as inspection systems.

The first seven chapters are dealing with the basic theory of the wheel rail interface and track design. In the design attention is given to both static and dynamic aspects, whereby a number of examples is given of results obtained from computer models like RAIL, GEOTRACK and ANSYS. In the part on stability and longitudinal forces the CWERRI program is extensively discussed.

The discussion of track structures has been split up into a chapter on ballasted track and one on slab track. The first one is dealing with the conventional structures and modern ballasted designs, whereas the slab track chapter focuses on developments of the last decades. Both continuous slabs and prefabricated solutions are addressed in combination with discretely supported and continuously supported rails.

The chapter on rails has been brought to the state of the art, with introducing the new EN standards and discussing the latest inspection systems. Also the latest information on bainitic rail steels has been incorporated.

For switches and crossings high-speed turnouts are discussed, together with the geometrical design criteria, and also modern inspection systems for controlling switch maintenance.

In railway engineering practice track maintenance and renewal forms a key factor. The latest track maintenance methods and the associated machines are presented, being a major extension compared to the first edition of this book. The part on track deterioration has now been incorporated in this chapter.

Optimization was one of the issues very much underestimated in railway engineering. Such techniques are not only applicable to components and structures, but also to decision support systems and resource optimization. A separate chapter has been added called numerical optimization with the main emphasis on structural components.

From the outset railway engineering has always had a strong component in experimental work. Therefore a new section has been added on testing and acceptance, in which also the issue of acceptance criteria for new railway components is addressed.

The chapter on noise and vibration is describing the fundamentals and has been taken over from the first edition with only a few modifications.

The chapter on inspection and detection methods has been completely revised. The original chapter was primarily based on NS experience. Now the state of the art inspection systems have been introduced. However the fundamental parts of the first edition have been left in tact.

The chapter on high-speed tracks contains some applications of high-speed projects and some dedicated issues such as pressure waves in tunnels. Also a section is devoted to magnetic levitation.

In track maintenance management systems various issues on track maintenance and renewal decision support are described, as well as monitoring of phenomena relevant to the various maintenance processes. Special attention is given to the ECOTRACK system, developed under the auspices of UIC and maintained and supported by TU Delft.

Railway assets involve a large capital and need to be managed carefully. The chapter on this issue deals with the general principles of asset management and the way in which such systems can be set up.

The final chapter is dealing with life cycle cost analysis. After describing the general principles a number of case studies are discussed.

Zaltbommel, Summer 2001

Coenraad Esveld

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1 INTRODUCTION

1.1 Historic development

The rail as supporting and guiding element was first utilised in the sixteenth century. In those times the mines in England used wooden roadways to reduce the resistance of the mining vehicles. The running surface was provided with an uprising edge in order to keep the vehicles on the track.
During a crises as a result of overproduction in the iron industry in England in 1760, the wooden rails were covered with cast iron plates which caused the running resistance to diminish to such an extent that the application of such plates soon proliferated. About 1800 the first free bearing rails were applied (Outtram), which were supported at the ends by cast iron sockets on wooden sleepers. Flanged iron wheels took care of the guiding, as we still practice now. In the beginning the vehicles were moved forward by manpower or by horses.

The invention of the steam engine led to the first steam locomotive, constructed in 1804 by the Englishman Trevithick. George Stephenson built the first steam locomotive with tubular boiler in 1814. 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.

The railways formed a brand new means of transportation with up till then unknown capacity, speed, and reliability. Large areas were opened which could not be developed earlier because of the primitive road and water connections. The railways formed an enormous stimulus to the political, economical and social development in the nineteenth century. Countries like the United States and Canada were opened thanks to the railways and became a political unity. In countries like Russia and China the railway still plays a crucial roll.

The trade unions originated when the railways were a major employer (railway strikes in England in 1900 and 1911 and in The Netherlands in 1903). The railway companies were also the first line of business which developed careful planning, organisation and control systems to enable efficient management. Moreover, they gave the impulse to big developments in the area of civil engineering (railway track building, bridges, tunnels, station roofing).

1.2 Railways

While the railways found themselves in a monopoly position up to the twentieth-century, with the advent of the combustion engine and the jet engine they had to face strong competition in the form of buses, cars and aeroplanes.

Mass motorization after World War II expressed by the growing prosperity brought about many problems, especially in densely populated areas: lack of space, congestion, lack of safety, emission of harmful substances and noise pollution. Exactly in these cases railways can be advantageous as they are characterized by the following:

– Limited use of space compared to large transport capacity;

– Reliability and safety;

– High degree of automation and management;

– Moderate environmental impact.

- Track must be constructed in such a way that the trains running on it do not cause excessive environmental pollution in the form of noise and ground vibrations.
- Costs of the total service life of the track must be as low as possible.
- Maintenance should be low and as inexpensive as possible.

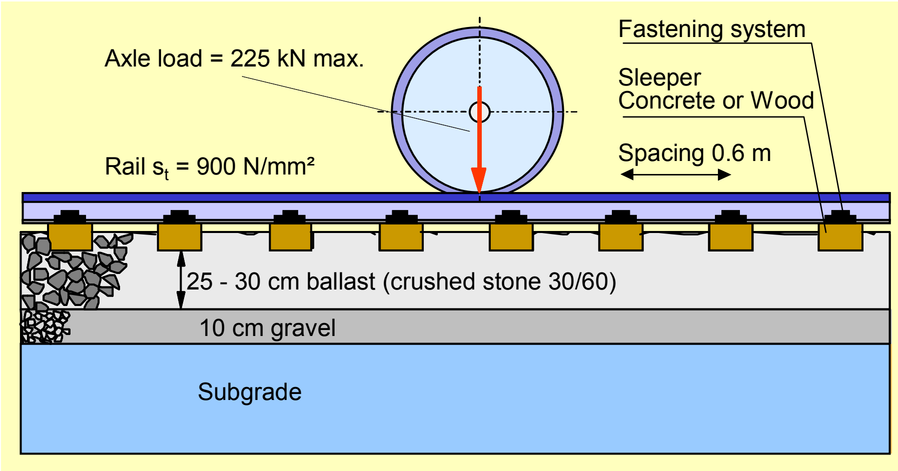

Figure 1.8: Conventional track structure

Tracks and switches are assets which will last for quite some years. The choice of a particular track system and the decision to use this system on certain lines, therefore, generally involves a decision which will hold good for 20 to 50 years. Consequently, such decisions must be taken with the future in mind, however difficult it may be to make a valid prediction. The only sure factor is that a certain degree of objectivity must be maintained vis-à-vis the present day situation, and not too much emphasis placed on random everyday events.

When choosing a track system, the above-mentioned requirements must all be given due consideration and it is clearly necessary to form some idea of the axle loads and maximum speeds to be expected in the decades to come. After this the situation regarding the various track components, such as rails, sleepers, fastenings, switches, and ballast should be examined so that the optimum track design is obtained.

1.6.2 Load-bearing function of the track

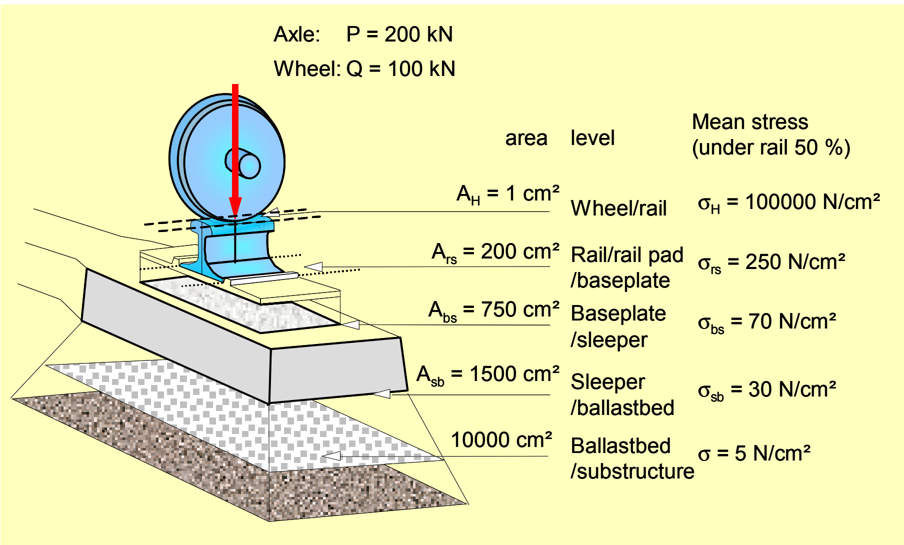

Figure 1.9: Principle of load transfer

The purpose of track is to transfer train loads to the formation. Conventional track still in use consists of a discrete system made up of rails, sleepers, and ballastbed. Figure 1.8 shows a principle sketch with the main dimensions.

Load transfer works on the principle of stress reduction, which means layer by layer, as depicted schematically in Figure 1.9. The greatest stress occurs between wheel and rail and is in the order of 30 kN/cm^2 (= 300 MPa). Even higher values may occur (see chapter 2). Between rail and sleeper the stress is two orders smaller and diminishes between sleeper and ballast bed down to about 30 N/cm^2. Finally the stress on the formation is only about 5 N/cm^2.

When spin takes place, the relative movements between wheel and rail will also partly be taken up by elastic distortion and partly by slip. The result will be that in the contact area forces are generated with varying magnitude and direction, the resultant of which produce a force in the lateral direction. This can be clarified by means of Figure 2.24.

In this picture, which was used in numerical considerations about contact mechanics, the contact ellipse is divided into a grid of small elements. Each element shows the magnitude and direction of the slip regarding that element.

The resulting lateral force that acts on the wheel is directed to the 'high' side. Here too, small values of the force increase linearly with the magnitude of the spin. However, for a certain value of the spin a maximum is reached which decreases with the subsequent increasing of spin values.

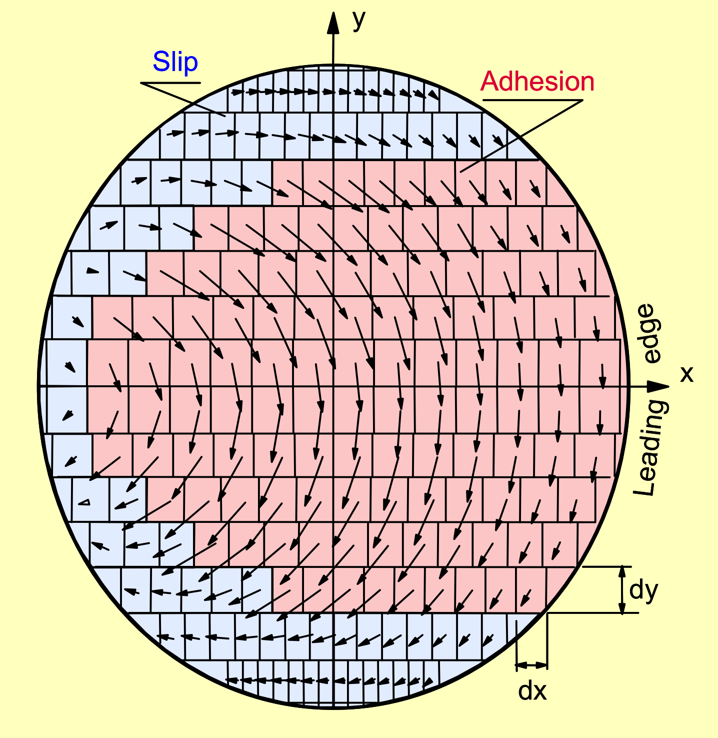

Figure 2.24: Origination of pure spin

A typical effect of this spin force is the almost complete compensation of the lateral component of the normal force for low values of the conicity. Hence the expected spreading of both rails by the lateral components of the normal force will be much less.

With greater values of the creep and slip these relations will not only be non-linear, but mutual influences also exist which make the connections much more complicated.

2.7.7 Creepage coefficients

According to Kalker [147], for both creep and spin it may be assumed that for small values the relations between these quantities and the resulting generated forces are about linear and can be expressed by:

$$T_x = Gc^2 C_{11} \varepsilon_x \tag{2.17}$$

$$T_y = Gc^2 (C_{22}\varepsilon_y + C_{23} c\phi) \tag{2.18}$$

$$M_z = Gc^3 (C_{23}\varepsilon_y + C_{33} c\phi) \tag{2.19}$$

with:

G = shear modulus
c = geometric mean of semi-axes of contact ellipse: $c = \sqrt{ab}$
C_{ij} = the so-called Kalker coefficients: constants determined by the ratio between the semi-axes a and b and the normal force N on the contact area.

In Table 2.2 the Kalker coefficients are given for the friction forces T_x and T_y (the moment M_z is disregarded).

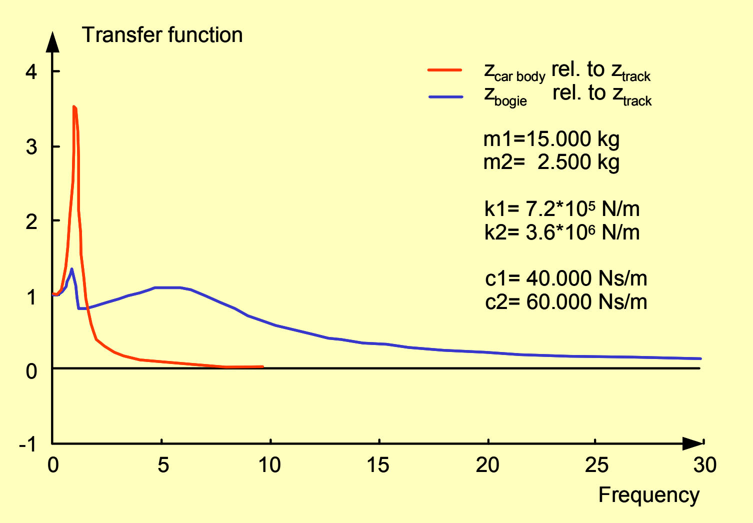

Figure 3.15: Response function of train (ICE) moving at 300 km/h

The output of the model is obtained by multiplying the spectrum of the input by the response function. The displacements and rotations of a car body as well as the acceleration required to estimate the comfort are then calculated in a time domain using the reverse Fourier Transformation. More information on the dynamic analysis in the frequency domain are discussed in Chapter 6. Two illustrative cases using the PASCOM model are described below.

3.10.2 Case 1: Investigation of dynamic effects

In order to demonstrate the effect of dynamic effects, the behaviour of two vehicles with and without suspensions moving on a curve track (Figure 3.16a) has been analysed. The vehicle without suspensions (or with infinitely stiff suspensions) represents the quasi-static model. The vehicle with suspensions is one of the ICE trains. Here, the theoretical cant has been used, i.e. the one when the passenger is not affected by the lateral accelerations. Clothoids have been used for both transition curves and super-elevation ramps resulting in a linear variation of cant. The results of simulation as function of the distance (s) along the curve are shown in Figure 3.17 and Figure 3.18. Figure 3.17 clearly shows that the behaviour of a rigid vehicle is completely determined by the geometry of a track. The lateral displacement and rotation of a car body can be derived from the angle of cant (Figure 3.16b). According to this model of a vehicle, a passenger can only feel the accelerations in the beginning and in the end of the transitional curves corresponding to the peaks in Figure 3.17c

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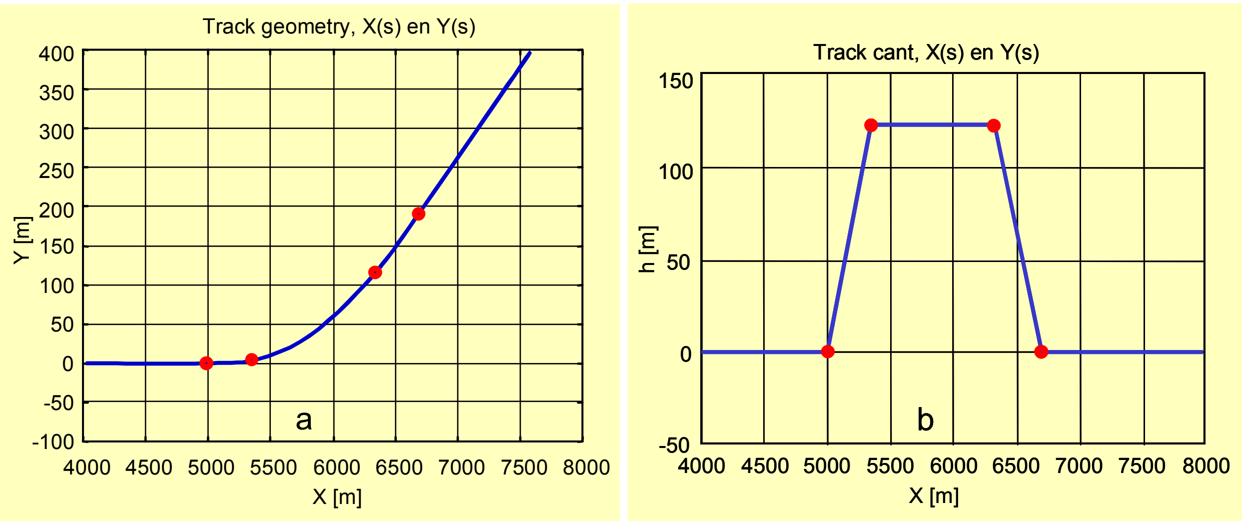


Figure 3.16: Track geometry: horizontal plane (a) and cant (b)

5 STATIC TRACK DESIGN

5.1 Introduction

The subject of this chapter is track dimensioning, the main point of which is to ensure that the track structure is suitable for the loads it has to carry and the resultant stresses and deformations. Conventional track calculation is limited to quasi-static loading of the track structure, schematized as an elastically supported beam. To the static load is added a dynamic increment. Details on rail stresses as a result of contact pressure have been given earlier. Fatigue and high frequency loads at welds or caused by wheel flats are dealt with in chapter 6 on dynamic track design.

5.2 Supporting models

5.2.1 Winkler support model

Conventional track consists basically of two parallel continuous beams, the rails, which are fixed at regular intervals onto sleepers supported from below and from the side by a medium which cannot be deformed, the ballast bed. In turn, the ballast bed rests on a formation which also cannot be deformed [292]. In elementary calculations it is usually presupposed that the Winkler hypothesis applies to track support; this hypothesis was formulated in 1867 and reads: at each point of support the compressive stress is proportional to the local compression. This relation is illustrated in Figure 5.1 and can be written as:

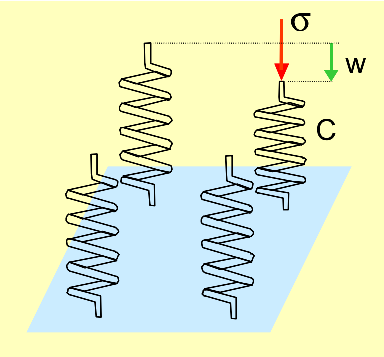


Figure 5.1: Winkler support model

$$\sigma = Cw \tag{5.1}$$

in which:

σ = local compressive stress on the support [N/m²];
w = local subsidence of the support [m];
C = foundation modulus [N/m³].

5.2.2 Discrete rail support

Let us consider the situation of a discretely supported rail (Figure 5.2). Between the vertical force $F(x_i)$ on a support number at $x = x_i$ with effective rail support area A_{rs} and the deflection $w(x_i)$, the following relation exists according to Winkler:

$$F(x_i) = CA_{rs}w(x_i) = k_d w(x_i) \tag{5.2}$$

Hence the spring constant of the support is:

$$k_d = CA_{rs} \tag{5.3}$$

Determining the spring constant in a railway track with a homogeneous support is relatively simple using the equilibrium condition:

$$k_d = \frac{\Sigma F}{\Sigma w} = \frac{Q}{\Sigma w} \tag{5.4}$$

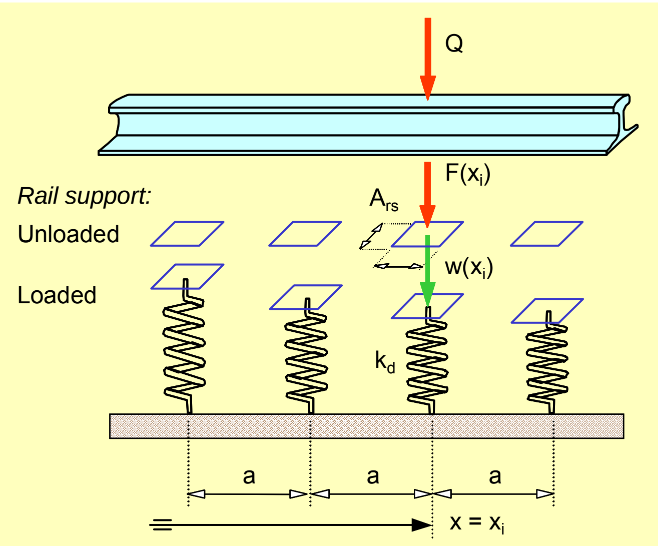


Figure 5.2: Discrete elastic support model

5.11 Two Case ERS designs

5.11.1 Testing of the UIC54 ERS

Several case studies were performed at the Technical University Delft using the ANSYS software on ballastless track structures with a special concentration on the Embedded Rail Structure (ERS). Initial calculations of ERS using the ANSYS program were made with the "standard" ERS, i.e. the ERS with UIC 54 rail, Edilon prefab elastic strip nr. 102, and Edilon Corkelast compound VA60, as shown in Figure 5.30. The aim of this investigation was to devise and calibrate a numeric FEM-based model of ERS, which could be reliably used in future to reduce the number of long and expensive laboratory tests.

Figure 5.30: Standard UIC 54 Embedded Rail Structure

Test	Angle	Load	Type of Load
1a	0°	V=*P*	Static
1b	0°	V=*P*	Static & dynamic
2	22°	V=*P*; H=0,4•*P*	Static & quasi-static
3	31°	V=*P*; H=0,6•*P*	Static & quasi-static
4	0°	V=*P*	Static

Table 5.11: Tests determining the elasticity

The calibration of the model was performed by comparing the obtained numeric calculation results with the ones previously obtained in laboratory. Applied loads complied with the NS regulations regarding testing of the track elasticity of Embedded Rail Structures, i.e. with the loads applied in the vertical, sloped (22 and 31 degrees), and longitudinal direction, as shown in Table 5.11 and in Figure 5.31. Some of the essential results of this study were:

- The ANSYS FEM calculation could reliably describe the results of laboratory tests on stiffness and strength of ERS, hence it could be used instead of multiple testing of intermediate designs. Thus, the laboratory work can be restricted to only performing tests on the final design.

- The obtained results not only staid within a 5% margin, but were even less compared to the laboratory tests. This means that the ANSYS FEM calculations could be successfully used to reduce the laboratory tests. However, calibration of the FEM with a corresponding laboratory test still remains a necessary prerequisite in order to use it.

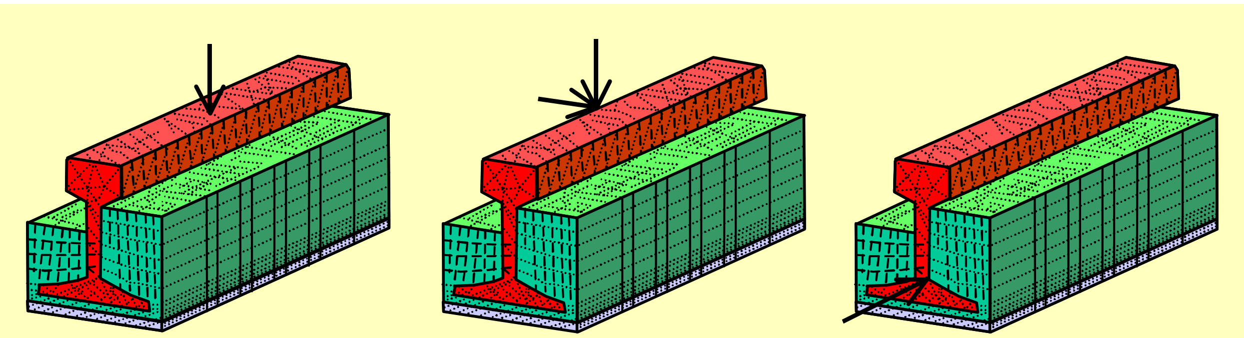


Figure 5.31: Testing with different loading cases

6 DYNAMIC TRACK DESIGN

6.1 Introduction

When dealing with track mechanics most of the problems are related in one way or another to dynamics. The dynamic interaction between vehicle and track can be described reasonably well in the vertical direction using mathematical models. Figure 6.1 gives an example of such a model made up of a discrete mass-spring system for the vehicle, a discretely supported beam to describe the track, and a Hertzian spring acting in the wheel/rail contact area.

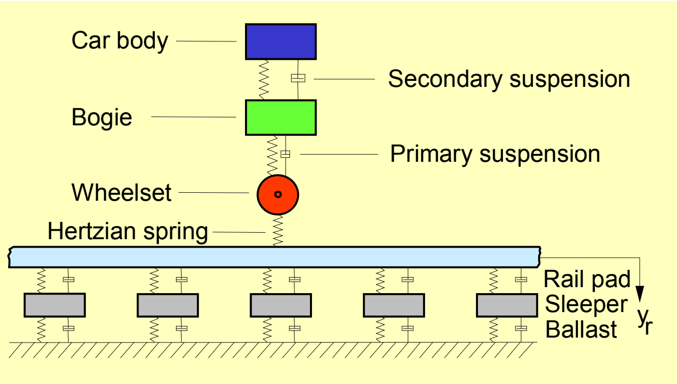


Figure 6.1: Dynamic model of vehicle-track interaction

Dynamic behaviour occurs in a fairly wide band ranging from very low frequencies of the order of 0.5-1 Hz for lateral and vertical car body accelerations to 2000 Hz as a consequence of geometrical irregularities in rails and wheel treads. The suspension system between wheelset and bogie is the first spring/damper combination to reduce vibrations originating from the wheel/rail interaction and is therefore called primary suspension. The reduction of the vibrations of lower frequency is dealt with in the second stage between bogie and car body and is called secondary suspension. This terminology can be applied to the track part of the model in the same way. The railpad and railclip represent the primary suspension of the track and the ballast layer or comparable medium represent the secondary suspension of the track.

Actual dynamic calculation is, however, extremely complex and is by no means generally accessible. Most analyses are limited to quasi-static considerations. Real dynamic problems are for the most part approached in a very pragmatic way by carrying out measurements.

In this chapter attention is given to the basic ingredients of the dynamic behaviour of railway track. Section 6.2 deals with some fundamental aspects. The 1-mass spring system, presented in Section 6.2.2, can be regarded as the most elementary system with the aid of which a number of practical problems can be considered. Extensions can be made in two directions: the construction can be enhanced to a multi degree of freedom system, and the load can be made more complex in terms of impact loads, and loads with a random character.

In Section 6.3 the track is modelled with relatively simple beam models consisting of the beam on an elastic foundation, a double beam, and a discretely supported track structure. The transfer function between track load and track displacement is discussed. Also the effect of a moving load running on the track is considered, as the track is considered to be infinitely stiff.

Track and rolling stock should in fact not be considered separately, but as one consistent system. For this reason the interaction between vehicle and track is introduced here without going into all the details required for a full treatment of this complex matter. After the introduction of the Hertzian spring, the physics of which were discussed earlier in Chapter 2, the transfer function between wheel and rail is derived in Section 6.4. This relationship plays an important role when interpreting track recording car data.

In Section 6.5 a concept is developed from which the relevant vehicle reactions can be calculated in real time using transfer functions based on track geometry measured independently of speed. A transfer function represents the contribution made by a geometry component to a vehicle reaction in the frequency domain. Geometry components include cant, level, alignment, and track gauge, and vehicle reactions include Q forces, Y forces, and horizontal and vertical vehicle body accelerations.

For tracks of good quality the critical speed lies far beyond the operating speed, but with poor soil conditions or other mass/spring configurations the critical speed can be so low that special measures are required. In case the train speed approaches the wave propagation speed, the soil may experience a liquefaction type of phenomenon as seen in Figure 6.19. An actual measurement in track on soft soil is shown in Figure 6.20.

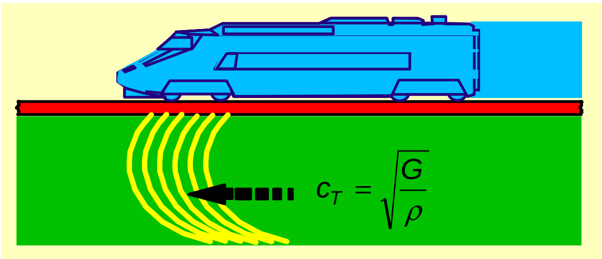


Figure 6.19: Wave propagation at high speed

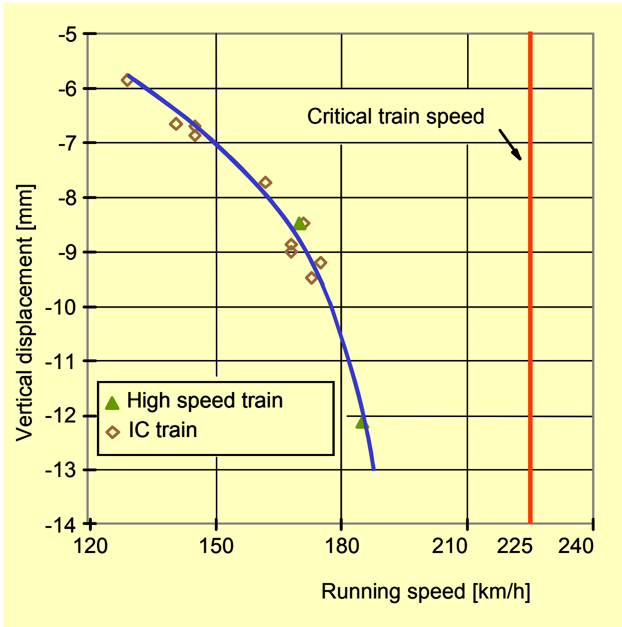


Figure 6.20: Actual measurement on soft soil

For the undamped case (left column of Figure 6.17) a simple formula exists [98] for the dynamic amplification:

$$\frac{w_{dyn}}{w_{stat}} = \frac{1}{\sqrt{\left|1 - \left[\frac{v}{v_{cr}}\right]^2\right|}} \qquad (6.56)$$

6.3.4 Discrete support

The model in Figure 6.10(c), in which the rail is supported in a discrete manner, gives the best approximation. Such an approach also lends itself to the application of standard element programs programs which will be discussed later in Section 6.9. These element method programs give great flexibility as regards load forms and support conditions.

6.4 Vertical wheel response

6.4.1 Hertzian contact spring

During vehicle/track interaction the forces are transmitted by means of the wheel/rail contact area. On account of the geometry of the contact area between the round wheel and the rail, the relationship between force and compression, represented by the Hertzian contact spring, is not linear as has already been discussed in Section 2.7. The relationship between force F and indentation y of the contact surface can be written as:

$$F = c_H y^{3/2} \qquad (6.57)$$

in which c_H [$Nm^{-3/2}$] is a constant depending on the radii and the material properties.

7 TRACK STABILITY AND LONGITUDINAL FORCES

7.1 Introduction

In conventional non-welded tracks the rails are connected by means of joints to allow for length changes caused by temperature fluctuations. Using joints prevents the development of axial forces and the consequent risk of track buckling at high temperatures. However, the penalty for this is the care for maintenance-intensive joints which generate high dynamic loads during train passage. These loads are responsible for many problems like rapid deterioration of vertical track geometry, plastic deformation of the rail head, dangerous rail cracks as well as damage to sleepers and fastenings. These problems increase progressively as speed increases. As a rule, joints have a very considerable negative effect on the service life of all track components.

Tracks with continuous welded rails (CWR) do not possess the above drawbacks. Owing to the absence of joints the quality of the track geometry is better by an order and this results in a substantial decrease in the total life cycle cost. CWR does not, however, only have advantages. As was pointed out in Chapter 5, the stresses resulting from the plane strain situation may be of the order of 100 N/mm² and should be added to the residual rail stresses and bending stresses caused by train loads which are of the same order of magnitude. Temperature stresses especially are responsible for failure of welds with small imperfections at low temperatures. On the other hand, lateral stability should be sufficiently great to resist compression forces developing at temperatures above the neutral temperature of 25°C, as buckling may otherwise occur as, for example, illustrated in Figure 7.1. The principle of this phenomenon is sketched in Figure 7.2 showing the compressive forces and the resistance forces on the track and the resulting typical buckling shape.

Figure 7.1: Example of track buckling

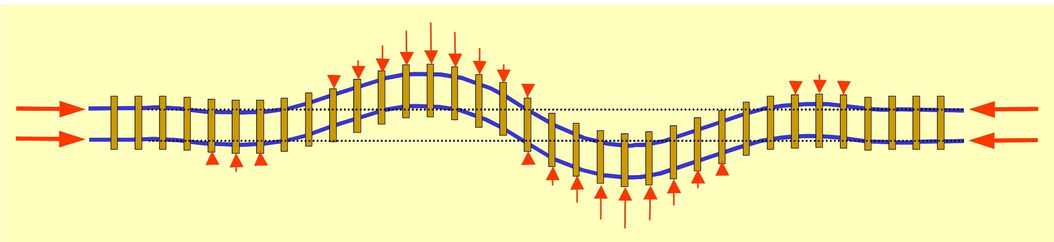


Figure 7.2: Typical buckling shape

On bridges and viaducts the deformation regime deviates from the plain track situation. The rails follow the construction which can undergo large displacements with respect to the adjacent track. Without adequate measures this would result in high rail stresses. To avoid these stresses expansion joints are applied.
This chapter is devoted to track stability and track longitudinal problems which, in the case of compression forces, are strongly interrelated. For both fields analytical and finite element modelling approaches are presented with examples. The last section discusses recently developed advanced models which describe safety considerations about track buckling or deal with more general or complicated track systems.

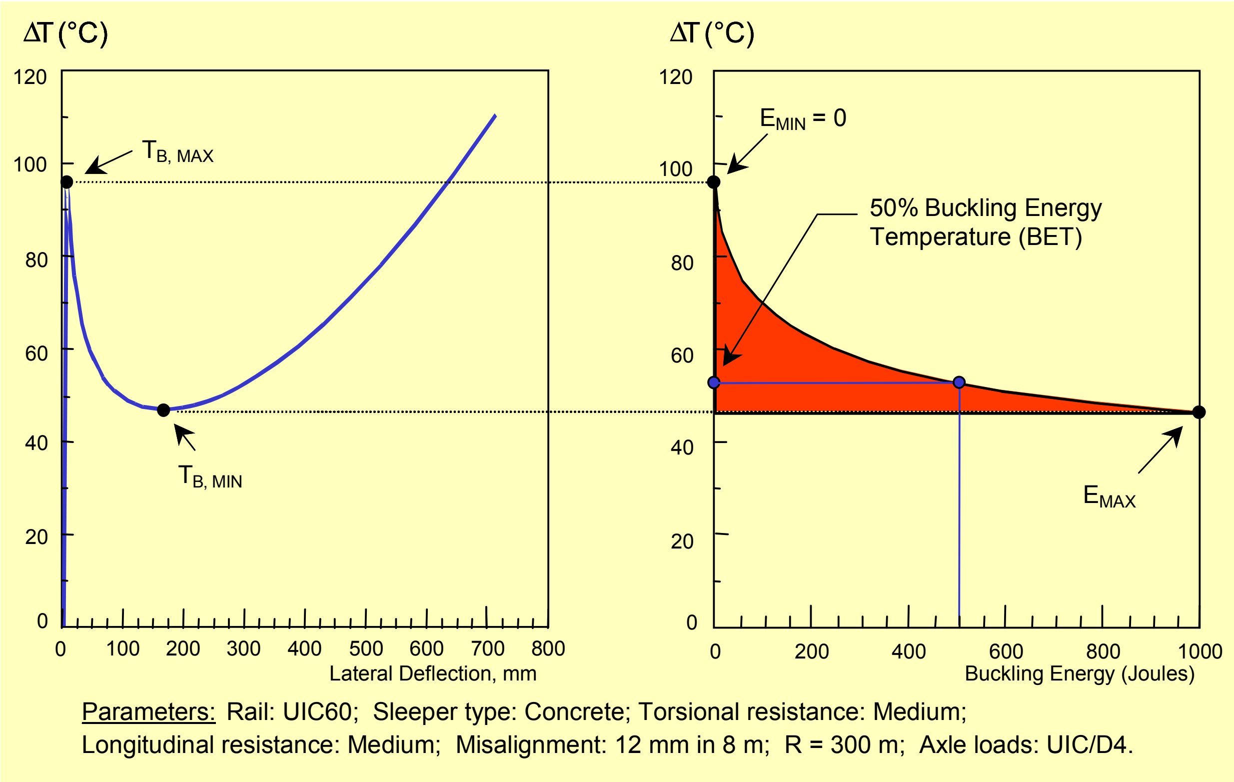


Figure 7.47: Buckling energy concept illustration

Approach 1 for determining ΔT

In this approach, the buckling energy versus temperature increase relationship is used as a criterion for choosing ΔT, e.g. Level 2. Safety is based on an allowable temperature which corresponds to a temperature at which a finite buckling energy exists that is larger than zero but less than the maximum value at $T_{B,MIN}$. Determination of the buckling energy is based on a program called CWR-BUCKLE from US DOT (Department Of Transportation). Research to date suggests using the 50% Buckling Energy Level (BEL):

$T_{ALL} = T_{50\%BEL}$

Approach 2 for determining ΔT

If the CWR-BUCKLE model is not available for determining the buckling energy, an alternative definition of ΔT may be based on the model prediction of $T_{B,MAX}$ and $T_{B,MIN}$. The program CWERRI can be used to determine these levels. This safety concept was recently incorporated into UIC Leaflet 720 through ERRI D202. The results can be summarized as follows:
For all CWERRI calculations: first calculate $\Delta T = T_{B,MAX} - T_{B,MIN}$:

if $\Delta T > 20$ °C: $T_{ALL} = T_{B,MIN} + 25\%$ of ΔT;
if 5 °C < $\Delta T < 20$ °C: $T_{ALL} = T_{B,MIN}$;
if 0 °C < $\Delta T < 5$ °C: $T_{ALL} = T_{B,MIN} - 5$ °C;
if $\Delta T < 0$ °C: Not allowable in main lines.

In the last case progressive buckling (PB) occurs which means that elastic and plastic lateral deformation easily fade into each other. PB is common in low ballast quality structures.

8 BALLASTED TRACK

8.1 Introduction

This chapter deals with the principles according to which ballasted track, also called ’classical track’ or ’conventional track’, is constructed. A detailed discussion of every type of track structure and its variants is beyond the scope of this book. Only a few examples will be given with the main intention of illustrating the principles.

The classical railway track basically consists of a flat framework made up of rails and sleepers which is supported on ballast. The ballast bed rests on a sub-ballast layer which forms the transition layer to the formation. Figure 8.1 and Figure 8.2 show the construction principle of the classical track structure. The rails and sleepers are connected by fastenings. These components and other structures such as switches and crossings are all considered as part of the track. The particulars of switches and crossings are discussed in Chapter 11.

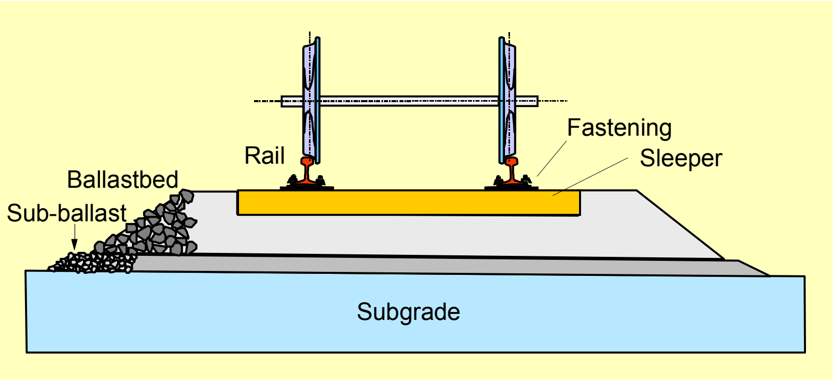


Figure 8.1: Principle of track structure: cross section

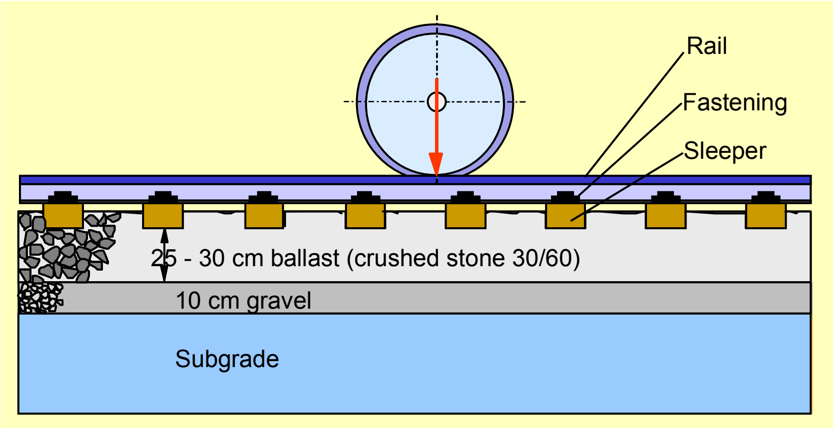


Figure 8.2: Principle of track structure: longitudinal section

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: introduction of continuous welded rail, use of concrete sleepers, heavier rail-profiles, innovative elastic fastenings, mechanisation of maintenance, and introduction of advanced measuring equipment and maintenance management systems. As a result, the traditional ballasted superstructure can still satisfy the high demands, as demonstrated by the TGV-tracks in France.

8.8.4 Elastic fastenings

The introduction of CWR track gave rise to the need for fastenings with greater elasticity. Certainly in the case of concrete sleepers, which are susceptible to impacts, this is an absolute necessity. Since the end of the fifties the NS has used the DE clip (Deenik, Eisses). This component is fitted to both timber sleepers and concrete sleepers as shown for instance in Figure 8.15. The DE clip, which can also be used in combination with baseplates, is usually fitted in a holder. The clip holder is fixed to the sleeper by means of pins which are cast into concrete sleepers or, as in the case of timber sleepers, are pushed into pre-drilled holes.The DE clip is installed using special equipment.

As there is no threaded screw connection, in principle no maintenance or adjustment is theoretically required. But this so-called 'fit-and-forget' principle also implies a drawback. If manufacturing tolerances are not met or if excessive wear occurs, there is no means of adjusting the fastening.

Figure 8.22: Effect of sleeper treatment with araldite

Other examples of elastic fastenings are the Pandrol standard clip, shown in Figure 8.23, the Pandrol Fastclip, shown in Figure 8.24, the Vossloh fastening, shown in Figure 8.25, and the Nabla clip, depicted in Figure 8.26.
i

Figure 8.23: Pandrol fastening system

Figure 8.24: Pandrol Fastclip

Figure 8.25: Vossloh fastening system

Figure 8.26: Nabla fastening system

9 SLAB TRACK

9.1 Introduction

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

Experiences in high-speed operation have revealed that ballasted tracks are more maintenance intensive. In particular, due to churning up of ballast particles at high-speed, serious damage can occur to wheels and rails, which is of course prevented in the case of slab track.

With the design of railway lines factors like life cycle cost, construction time, availability and durability play an increasingly important role. In this respect non-ballasted track concepts offer good opportunities. With the growth of traffic intensity it becomes more and more difficult to carry out maintenance and renewal work. On European networks, night time possessions often last no longer than 5 hours, or even less. Seen against this background, the current increase in the popularity of low-maintenance track designs is evident.

In the past new projects were mainly assessed on the basis of investment costs, whereas today the principle of life cycle costing is strongly emerging. As a result of these new attitude, ballasted track concepts will loose attractiveness in favour of slab track systems.

9.2 Ballasted track versus slab track

The general problem which occurs with ballasted track is the slow deterioration of the ballast material due to traffic loading. Ballast consists of packed loose granular material of which the grains wander, wear, and break up causing increasing geometrical unevenness and clogging of the ballast bed by fine particles which cause drainage problems. Therefore, regular maintenance is time after time needed to restore the track alignment.

Figure 9.1: Ballasted track ...

Figure 9.2: ... and slab track

Integrated techniques for slab track installation

In order to reduce the expensive construction costs a new installation concept was developed for Rheda 2000. By omitting the concrete trough, a complete step in the construction work sequence was eliminated. Application of the light twinblock sleepers significantly simplified their use at the construction site and at the same time enabled the mechanised installation of prefabricated track panels. Specially developed surveying techniques enhanced the cost effectiveness of the track installation process.

Figure 9.15: Track assembly, track on top of the concrete roadbed on the concrete roadbed (for the project Leipzig-Gröbers)

The installation of the Rheda 2000 system on earthworks begins with placement of a concrete roadbed by means of a slipform paver. In the case of engineering structures, the required protective and profile concrete is generally laid instead.

Application of the twinblock sleeper allows use of conventional track-installation processes. The foundation provided by the concrete base-sockets enables loaded construction vehicles to use the rails without difficulty before they are accurately positioned and secured in place. As a result, it is possible to lay the track in single-sleeper mode or in the form of assembled track panels.

The arrangement of the slab layer reinforcement within the sleeper lattice-truss makes it possible for installation of the reinforcement to take place at the exact same time the track is laid. In this process, the construction crew places the required reinforcing rods on the concrete roadbed and inserts them section at a time through the lattice-girder compartments as shown in Figure 9.15.

Figure 9.16: Alignment portals in the Leipzig-Gröbers project

Coarse and fine alignment of the track can take place with the aid of two techniques:

– By means of alignment portal (see Figure 9.16): the portal units are first put into position with their feet anchored securely into the concrete roadbed after which the formwork elements are secured. The crew checks the installation for correctness. Next, the rail head clamps are lowered into place and fixed onto the rail as the track panel will be lifted approx. 9 cm and roughly aligned to ± 0.5 mm. The surveying crew gives instructions for the necessary settings to be made by the respective portal spindles for the superelevation (cant). After the final adjustments the track panel is secured and cleared for the pouring of concrete.

10 THE RAIL

10.1 Introduction

As the rail is the most important part of the track structure a separate chapter is devoted to it. In Chapter 8 several basic functions have been discussed. In this chapter some fundamental aspects of the quality of rails are discussed, such as the rail manufacturing process, acceptance procedures, mechanical properties, flash butt and Thermit welding, control of weld geometry, required standards, rail failure types and rail defect statistics.

10.2 Modern rail manufacturing

Modern rail manufacturing technology is considered in the new standard EN 13674 of the European Community. Different to existing specifications, it is a performance based standard. Some of the manufacturing techniques are defined in order to ensure that the rail shows good service properties. The steel may be produced either by the basic oxygen process (BOF) or in an electric arc furnace, although the latter is currently not used in Europe. Ingot casting is no longer allowed. Secondary metallurgy is more or less standard practice. Vacuum degassing is mandatory in order to avoid rail breakage caused by flakes and non-metallic inclusions. The manufacturer has to apply a quality management system to ensure consistent product quality and to pass a qualifying procedure to become approved for delivery.

The rail manufacturing process consists of the following main parts as indicated in Figure 10.1:

– Blast furnace;

– Steel-making;

– Continuous casting;

– Rolling;

– Straightening;

– Measurements (ultrasonic, geometry, manual inspection);

– Final acceptance.

In the next part of this section some of these processes will be discussed in greater detail.

10.2.1 Blast furnace

Steel is in fact iron which has been refined with carefully measured amounts of other elements added to it. Iron is found as iron oxide in rocks, known as iron ore. This only occurs in sufficiently large quantities and with reasonable accessibility in a few scattered areas of the world, for the most part in Scandinavia, the Americas, Australia, North Africa, and Russia.

The ore is graded and crushed and some of the finer ore is taken to the sinter plant where it is mixed with coke and limestone and heated to form an iron-rich clinker known as sinter. This sinter is fed into the top of the blast furnace together with more iron ore, coke and limestone in controlled proportions, and the whole is fired. Great heat is generated and fanned to white hot intensity by blasts of superheated air.

Figure 10.3: Basic Oxygen Furnace (BOF) (Corus)

The positioning of the lances, the determination of the volume of oxygen to be injected, the additions to be made and the corrective steps required are computer-controlled and fully automated.

When all the steel has been tapped out into a ladle the converter is turned upside down and the residual slag is tipped into a waiting slag ladle for removal to a slag pool.

In the ladle the molten steel is carburized and alloyed. By means of the so-called secondary metallurgy the chemical composition is refined, the temperature adjusted and the cleanliness improved through decantation of inclusions.

Figure 10.4 shows a photograph of the filling process.

Figure 10.4: Filling proces of converter

10.2.3 Vacuum degassing and argon flushing

In the modern steel-making process several other steps are implemented to improve steel quality. Argon flushing facilities are used to homogenise temperature and chemical composition. Vacuum degassing units, such as depicted schematically in Figure 10.5, reduce the hydrogen content to less than 2 ppm and improve the oxidic cleanliness of the steel. With a hydrogen content of less than 2 ppm in the liquid steel no particular cooling measures are required to prevent the development of flakes. Under train loads these flakes can initiate fatigue cracks, an example of which is represented in Figure 10.69. (UIC code 211)

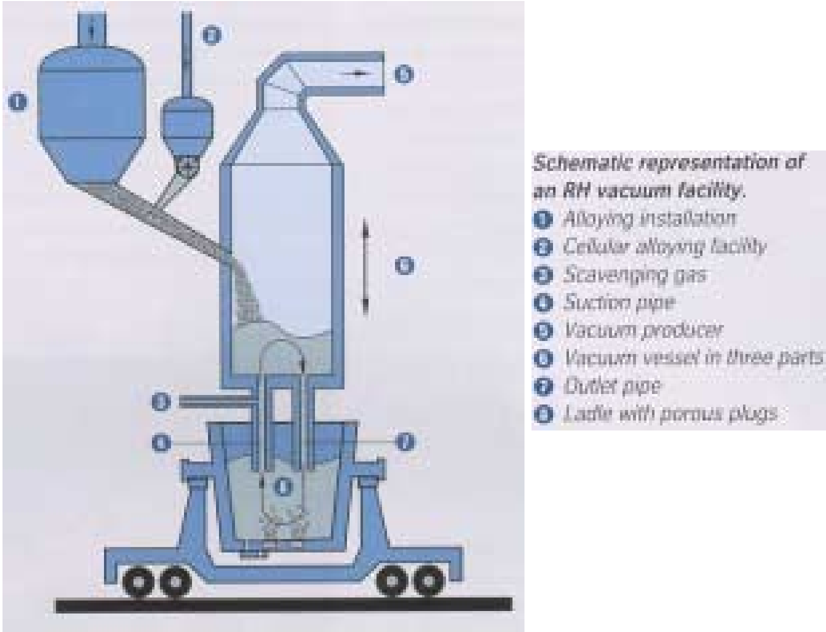


Figure 10.5: Schematic representation of a vacuum degassing unit (Thyssen)

10.2.4 Continuous casting

The principle of continuous casting, which is at present used by most of the steel works, is annotated in Figure 10.6. The liquid steel is supplied in a 150 - 350 tonne ladle which is placed in a turret. This turret can contain 2 ladles to practice sequencing of ladles. When the molten steel is poured from the ladle into the tundish the next ladle can be prepared.
In this way teeming may proceed continuously.

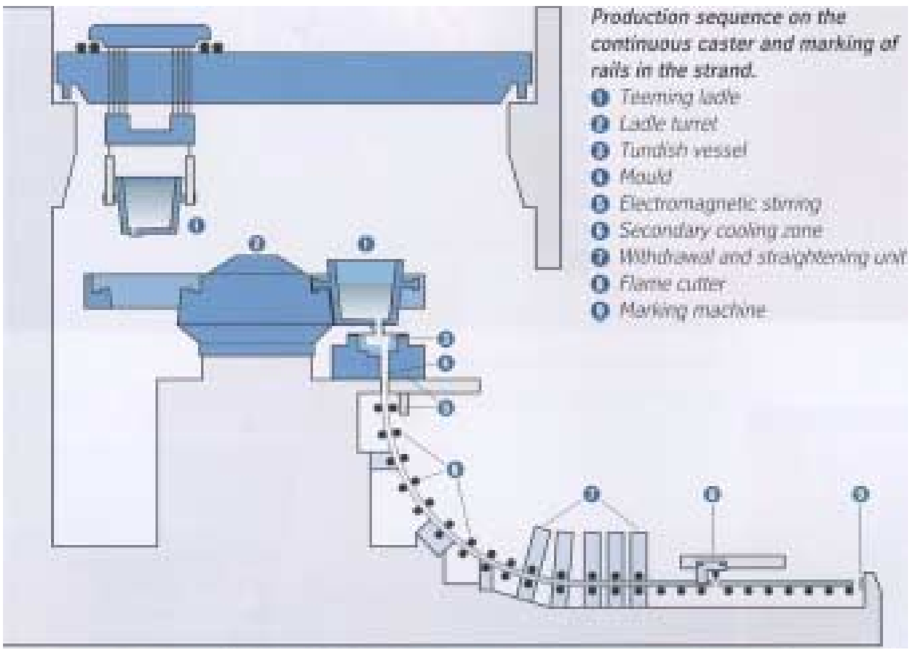


Figure 10.6: Principle of a Continuous Casting machine (Thyssen)

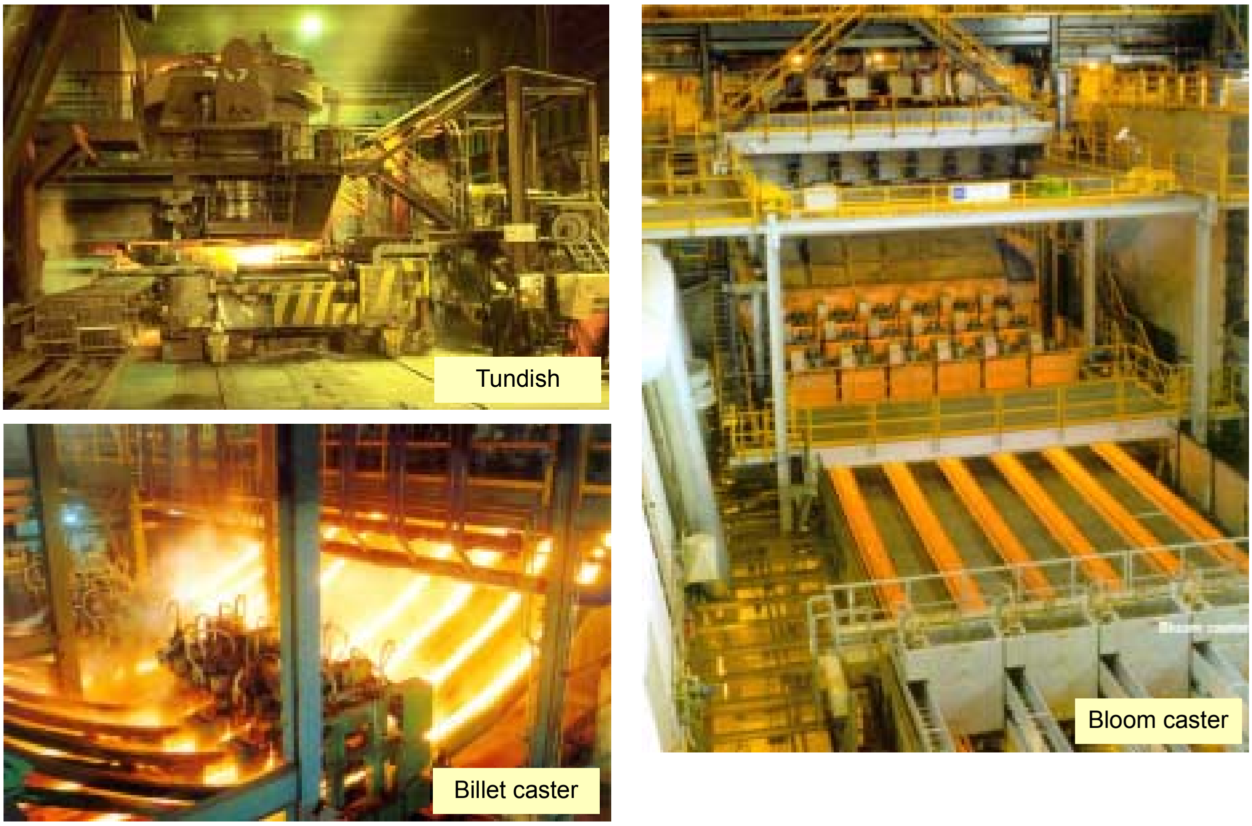


Figure 10.7: Some pictures of the continuous casting process

Figure 10.7 shows some pictures of a continuous casting facility. The liquid steel is cast from the ladle into the tundish using submerged pouring techniques. Metering nozzles are used to deliver precisely the right amount of steel to the 6 to 8 moulds.

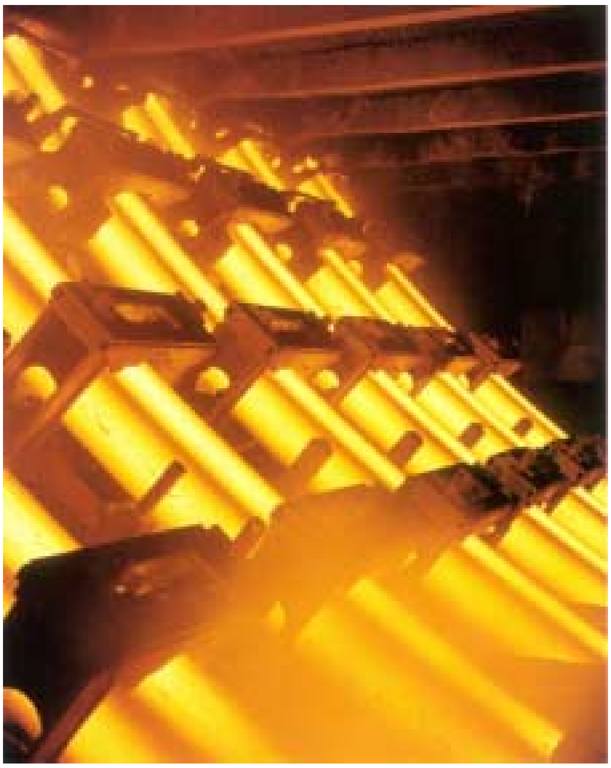


Figure 10.8: Hot strands passing through cooling chambers in a circular arc

All steel is protected from atmospheric oxidation by refractory tubes between ladle and tundish, and also between tundish and mould. The double-walled moulds are water-cooled. They shape the strands and may have different cross-sections.

Thyssen [18], for example, uses mould sections of 265 x 385 mm. The mould corners are chamfered to prevent corner cracking.

The amount of super-heat contained in the liquid steel has a profound effect upon the internal metallurgical quality of the cast bloom. The liquid steel temperature in the tundish is therefore maintained within the range liquidus plus 15 °C.

During casting the moulds oscillate with a frequency of 60 - 200 cycles per minute, depending on casting speed and oscillation stroke, to prevent the steel from adhering to the copper mould. The casting speed amounts to about 0.8 m/min. To improve the solidification structure the strands are equipped with electromagnetic stirring coils.

10.4.3 Post-processing of flash butt welds in the NS welding depot

In order to obtain a better geometry and higher fatigue strength values a number of additional steps following flash butt welding could be introduced according to the diagram of Figure 10.48 as originally applied in the NS welding Depot.
Directly after welding and stripping the hot weld is given a stress-free overlift of 2 mm on a 1.2 m base. This is done by a special press located 36 m in front of the welding machine.
During overlifting the weld is precooled with air in order to restore enough strength to avoid plastic deformation during transport to the next location.

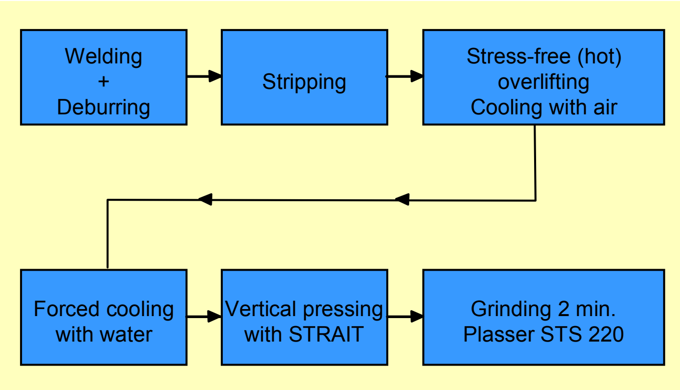


Figure 10.48: NS post-processing flash butt welds

There the weld is cooled with water which does not commence, however, until 4 minutes after welding to guarantee safe transformation for R 260 Mn (900 B) rails.

Figure 10.49: Press and operating console used at KHRC

At the next station a STRAIT-system reduces the 2 mm vertical overlift automatically to an overlift within the 0.1 - 0.3 mm interval. As a result of favourable residual compression stresses, the fatigue strength of the weld increases by about 8%. Figure 10.49 shows the press and the operating console. From this console the grinding process, which forms the finishing step, is also controlled.

Figure 10.50: Plasser & Theurer STS 220 stationary grinder

The STS 220 grinder, presented in Figure 10.50, is located 36 m ahead of the STRAIT machine. The STS 220 automatically grinds the weld vertically and horizontally for a period of 1.5 to 4 minutes, depending on the weld geometry measured by STRAIT.

11 SWITCHES AND CROSSINGS

11.1 The standard turnout

Turnouts are used to divide a track into two, sometimes three tracks. The purpose of crossings is to allow two tracks to intersect at the same level. If a complete train is to pass from one track to another while moving and without being subdivided, turnouts are essential in the absence of turntables or traversers.

It must be possible to run through switches and crossings in both directions. A normal or single turnout, as shown in Figure 11.1, allows movement of traffic in a straight direction on the through track or in a divergent direction. A picture of the right-hand turnout is given in Figure 11.2.

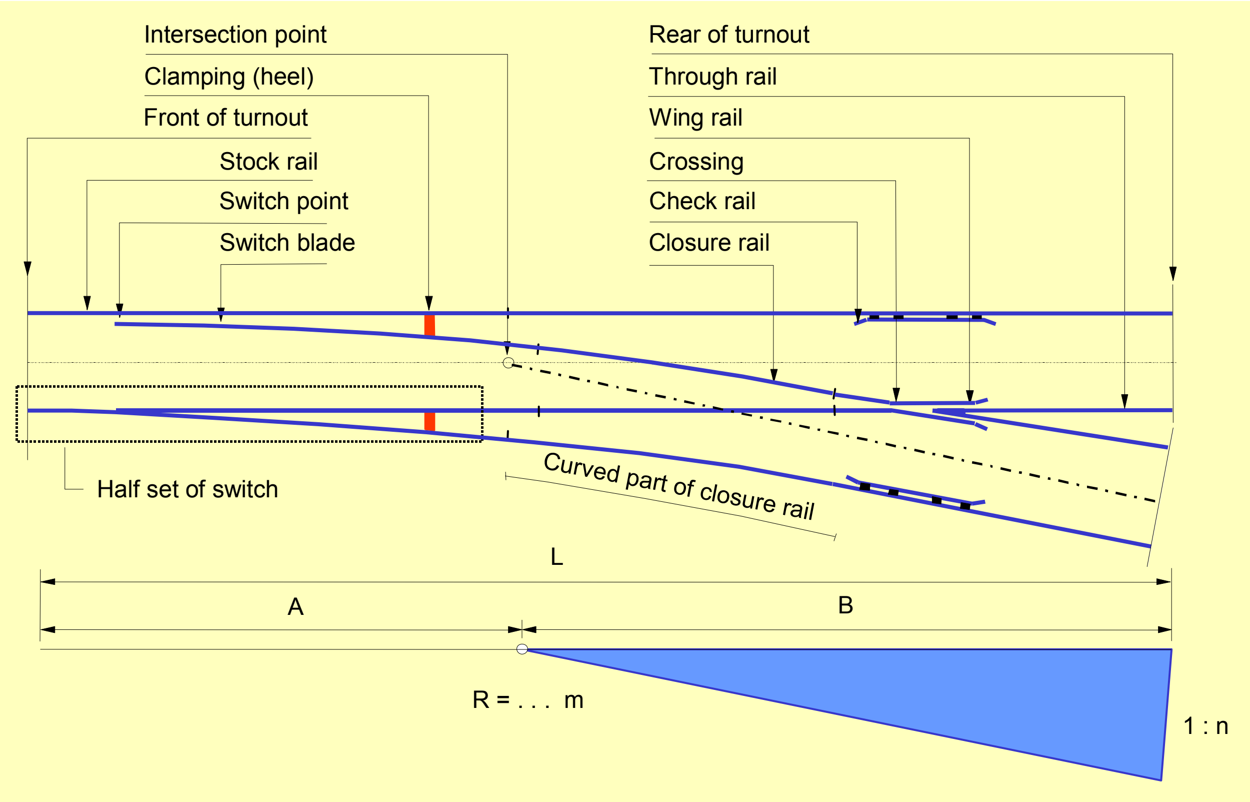


Figure 11.1: Standard right-hand turnout

The turnout consists of three major parts:

– Set of switches (switch blades);

– Common crossing;

– Closure rail.

These parts will be discussed separately below.

Figure 11.2: Picture of right-hand turnout

11.1.1 Set of switches

Switches consist of two switch blades and two stock rails. The switch blades can be moved and determine which of the above-mentioned tracks will carry traffic. In Figure 11.1 this is the through track.

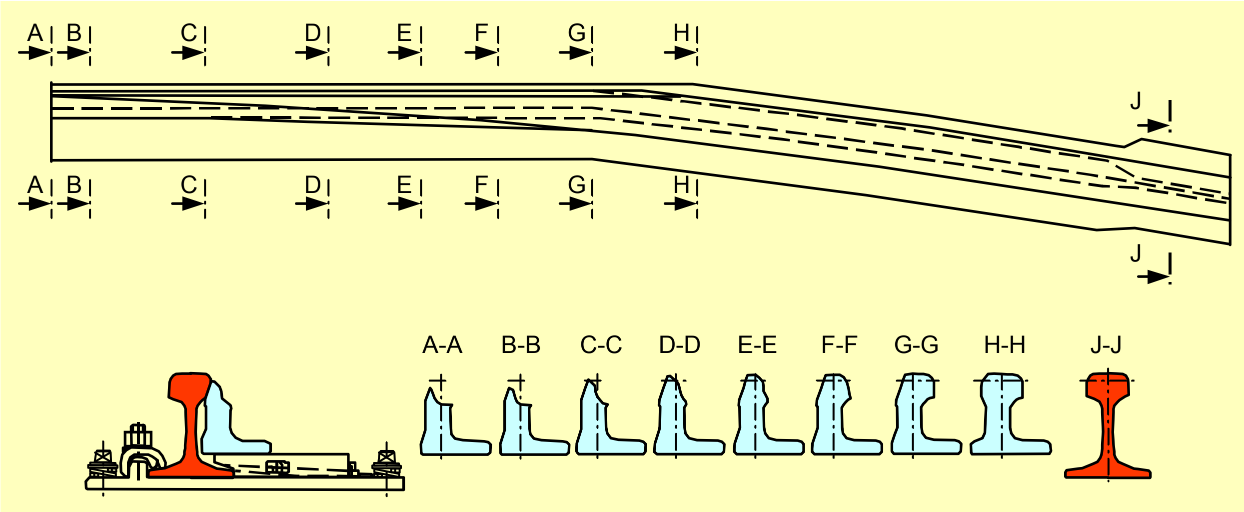


Figure 11.3: Cross-sectional drawing of switch blade and stock rail

Figure 11.4: Switch blade and stock rail

The cross-section of the switch blade in modern designs is an asymmetric section that is lower than the standard rail profile. This has the advantage that there very little machining of the base of the switch is necessary.

Because of the asymmetric base, the moment of inertia is higher compared to a switch blade made of standard rail. The lower height allows the use of an elastic fastening system for the stock rail on both sides which is a must in modern turnouts. Figure 11.3 and Figure 11.4 show an example.

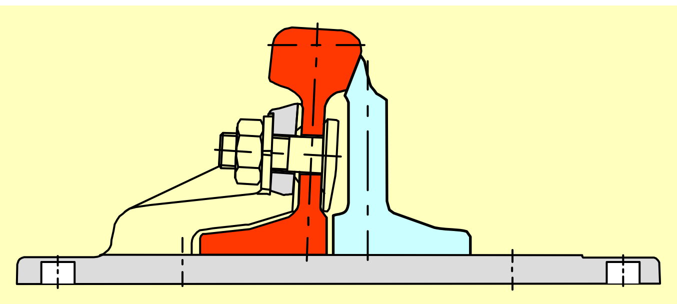


Figure 11.5: Cross-sectional drawing of T-rail switch blade

Some railways still use switch blades made of standard rails. Figure 11.5 shows the cross-section for such a turnout.

The turnout can be operated by different types of point machines, e.g. electrically, hydraulically or pneumatically. The locking system can be either in the switch machine (internal locking) or in the track (external locking). In switches for medium and especially for high speed several locking locations are necessary.

The smaller the angle of the switch the longer the switch blade is. The blade can get in contact with the wheel by passing a wheel through the gap between stock rail and blade. With a long blade extra locking is applied to prevent a switch blade from moving too much.

These lockings can either be operated by single point machines at each locking location or by one point machine at the toe-end of the switch and connecting rods that connect to the other locking stations. New developments for high speed or high capacity railway lines are integrated locking, switching, and detection systems.


Figure 11.6: Switch with integrated hydraulic setting and locking system

Figure 11.6 shows a new integrated hydraulic switching and locking system. Here the locking system is integrated in a hydraulic setting cylinder; no lubrication or maintenance is necessary. The principle of an integrated locking and switching machine enables the blades to move sequentially so less power is needed at the same time.
The blades and stock rail of the switch are heated by means of gas or electrical systems for protection in case of frost, snow or freezing rain.


Figure 11.7: Modern electrical point machine

Figure 11.7 shows a low maintenance electrical point machine. Preventive maintenance is only required once every five years. The tractive force can be adjusted between 2 and 10 kN. The locking unit is equipped with a spring function that gives the blade a contact force of 2.5 kN in the locked position. Sensors detect whether the blades are open or closed.

In modern railway systems the installations are operated from a central operating post.

11.1.2 Common crossing

Depending on the traffic load different types of crossings are used. For normal to medium axle loads and speeds up to 200 km/h rigid crossings are used. For higher axle loads and higher speeds crossings with movable parts have to be used.

The common crossing and the wing rails are built up geometrically in such a way that the passing wheel remains supported and wheel flange clearance is guaranteed. In a common crossing the intersecting rails form an acute angle.

In the common crossing the unguided part leads to an unquiet behaviour of the bogie in the switch and causes an extra dynamic load on the common crossing and on the check rail. To avoid unguided parts in the common crossing movable points should be used.

Several construction types of rigid crossings exist:

12 TRACK MAINTENANCE AND RENEWAL

12.1 Introduction

Track maintenance means the total process of maintenance and renewal required to ensure that the track meets safety and quality standards at minimum cost. Figure 12.1 gives a schematic summary of the various components, which go to make up the maintenance process. Annual maintenance on the NS network, with its 4500 km of main line tracks, comprises renewal of roughly 140 km of main line, 40 km of secondary tracks and sidings, 1000 km of mechanical tamping, 60 km of ballast cleaning, 10 km of corrective grinding and renewal of 250 switches. In addition to this the track requires spot maintenance on a daily basis.

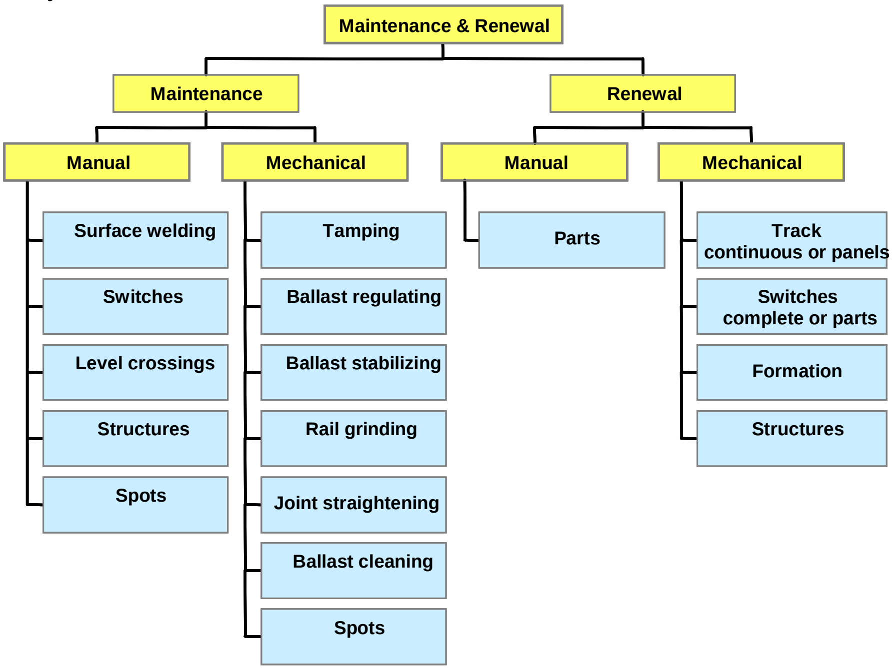


Figure 12.1: Schematic survey of maintenance and renewal process

Maintenance and renewal are in principle scheduled on the basis of control data from measuring systems, visual observation and financial-economic data, bearing in mind local conditions. The measuring systems are discussed in Chapter 16, and how the guidelines are obtained is explained in Chapter 18. This introduction concentrates on visual inspection and safety.

Visual inspection

The purpose of visual inspection is principally to check whether circumstances have arisen which may jeopardize safety of railway traffic. Inspection frequency varies depending on speed limit and daily train tonnage from a few times a week on the most important lines to once a month on the least important lines. Extra inspections are necessary in exceptional circumstances, such as very hot weather. Visual inspection becomes more and more supported by video inspection systems, which detect material faults by photo imaging (Chapter 16).

Safety

The braking distance of trains is much longer than that of cars or trams. Trains cannot be brought to a standstill in time if people or vehicles unexpectedly appear on the track. Similarly, it is not possible to halt traffic temporarily each time work is required on the track. This is why comprehensive stringent safety regulations apply to work within the structure gauge. Firstly the track must always be in a safe condition for approaching trains and secondly the safety of the track maintenance crews must be ensured.

Figure 12.6: Grinding units with rotating stones

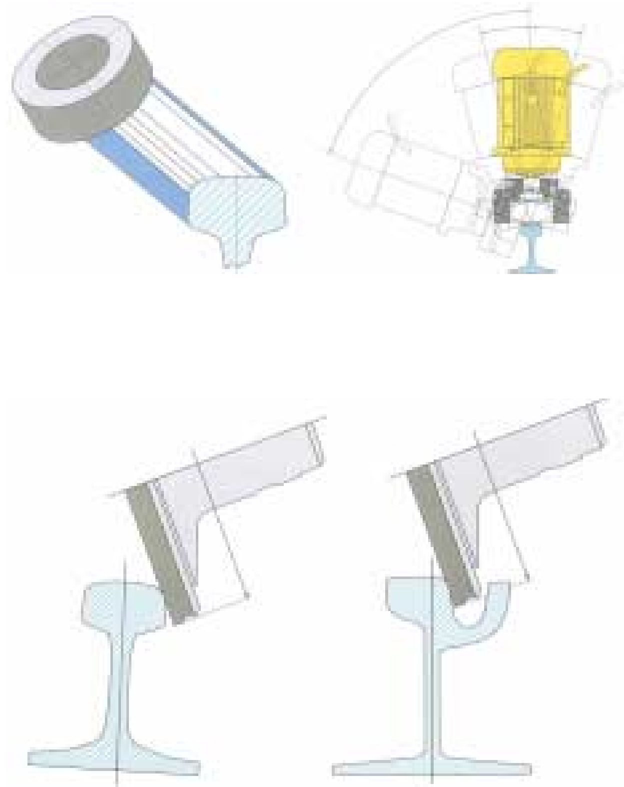


Figure 12.7: Principle of pivoting the Speno grinding units

A feature mainly applied on heavy haul railways is asymmetric grinding by means of which the wheel/ rail contact point is shifted towards the inside of the high rail and towards the outside of the low rail. This gives better steering of the wheelset by which flanging is prevented or at least reduced, thus lessening the problem of side wear, severe corrugations and shelling. Figure 12.9 shows the profiles of high and low rail which were ground asymmetrically with the Speno train. The shift of the contact is clearly visible and tallies with the applied principle. For more details on asymmetric grinding please refer to [157].

Figure 12.8: As-ground rail with the different facets clearly visible

Figure 12.9: Asymmetric ground rail profiles

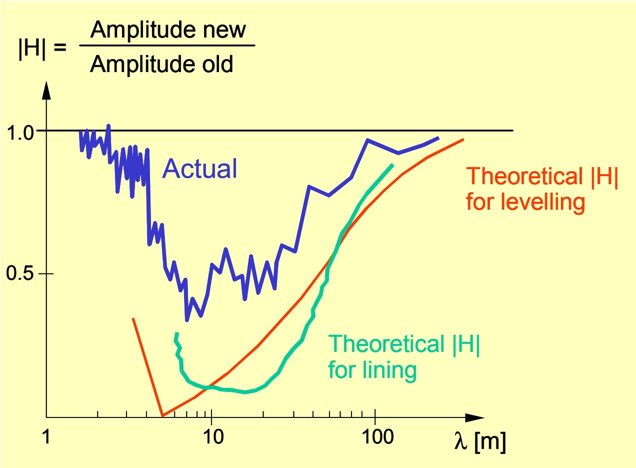


Figure 12.30: Comparison of theoretical and actual transfer function for 07-32 tamper

It should also be pointed out here that proportion of the initial improvement disappears again fairly quickly after tamping without additional stabilization.

Alignment

The lining system of modern track maintenance machines is based on a 4-point measurement, or, if design lining is applied, a 3-point measurement as is the case for vertical profile. In the 4-point system the machine measures three ordinates, Y_1, Y_2, and Y_4, as seen in Figure 12.31, which together determine a second-degree curve by means of which local track alignment is approximated. At work point C the track is aligned so that it comes to lie on this curve. The correct position is verified by means of versines h and H, the quotient of which has a fixed value.

If the machine is being used in the automatic mode the leading point of the long chord D follows the old track geometry whereas points A and B follow the geometry, which has just been corrected (Figure 12.32).

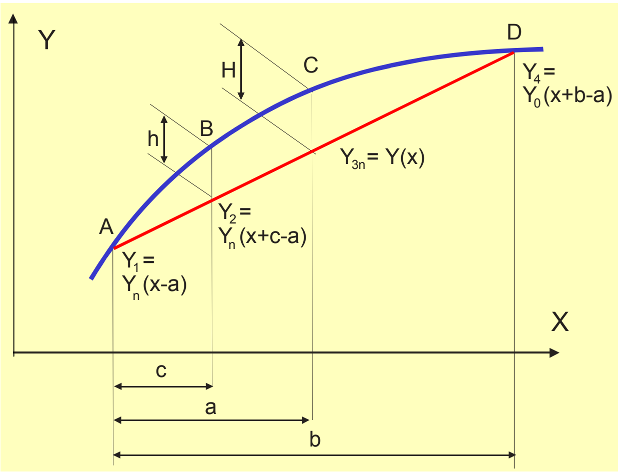


Figure 12.31: 4-point lining principle

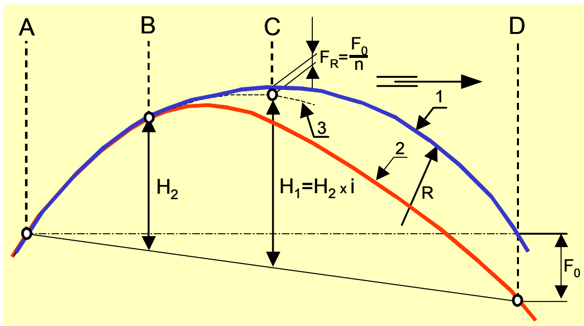


Figure 12.32: 4-point lining system with error F_0 at front end of lining chord

Design lining is also possible with these machines, in which case the new position must be defined beforehand. There are two options for supplying these data: the correction values are entered at D either manually or automatically by the on-board geometry computer (ALC) so that this point follows the ideal geometry. Minor errors in input values are smoothed out by the lining system of the machine.

The error reduction, which in theory can be achieved using the 4-point lining system, will be explained with the aid of Figure 12.31. Points A and B are already corrected points, for which the ordinates are indicated by Y_n (new). The location of the uncorrected point D is indicated by Y (old). If values a, b and c are known, the position of C can be expressed in that of A, B and D. In a similar way as for level the new geometry for alignment is to be expressed in the old according to the recursive relationship below:

$$Y_n(x) = \frac{a}{c}\frac{\alpha-1}{\alpha}Y_n(x-a+c) + \left[\frac{b-a}{b} - \frac{a(b-c)}{bc}\frac{\alpha-1}{\alpha}\right]Y_n(x-a) + \frac{1}{\alpha}\frac{a}{b}Y_0(x+b-a) \qquad (12.4)$$

Figure 12.44: Stoneblower operated at RAILTRACK

The grading was chosen to avoid any drainage problems and is also larger than the stone size associated with measured shovel packing.

Besides, the stone selected has a high mechanical strength and a low wet attrition value. It is placed in the area of highest stress in the ballast. The small size gives a greater number of contact points between the stones, thus lowering the contact stress and the possibility of breakdown. Inspections of stone blown track by means of lifting sleepers produced no evidence of the stones' breakdown. Furthermore, there had been no reports of any problems from any of the tracks treated over the long development period of the project. In fact, there is evidence that stone blowing improves the drainage properties of the track - probably by reducing the pumping effect of poorly supported sleepers.

12.7.2 Measuring philosophy used for the stone blower

For the stone blower process an algorithm was developed to produce a "design" geometry resulting in the most economical amount of material usage. The stone blower demanded a measuring system that was capable of surveying track geometry in sleeper-by-sleeper detail, covering track faults of up to 100 m length, including superelevation, at a speed of at least 40 km/h. The accuracy required was +/- 1 mm, and both loaded and unloaded profile were required.

Dedicated processors perform the essential tasks in which a machine control system (MCS) takes care of the logging and machine control functions, and a supervisory control system (SCS) performs the management and design functions.

The MCS collects the data at an exact measuring interval of 1.016 m and performs a number of validation checks to ensure that the information is correct. Data is then transferred to the SCS for conversion to an unloaded profile on completion of the measuring run. Table 12.1 shows an overview of stoneblower data.
The profile is additionally improved by considering the cross-axis sensitivity to track alignment that has a significant effect on the vertical profile, particularly when tight curve radii and large cants are involved. Ignoring this effect can cause errors, mainly in transitions. Both vertical and lateral profiles are created independently and they cross-reference to form profiles accurate in 3 dimensions with

The high energy caused locally in the track by the stabilizer can give rise to ground vibration on the line. Chapter 15 considers this in more detail. Operation on bridges and in tunnels is generally possible, certain operation parameters have to be observed.

12.10 Mechanised track maintenance train

Figure 12.56: Mechanised track maintenance train MDZ 2000

The aim of a complete continuous action, production-line treatment of the track with quality control of the completed work is achieved with the concept of a Mechanised Maintenance Train MDZ consisting of the levelling, lining, tamping machine, the ballast regulator and the dynamic track stabiliser. The last machine of the consist should also be equipped with a track recorder to document the finished job. The MDZ can be composed in different performance categories but it is important that the machines match in working and travelling speed. The standard consist of a MDZ for high capacity lines is shown in Figure 12.19.

By integration of ballast regulation into the tamping machine or the dynamic track stabiliser the MDZ consists only of two machines (Figure 12.56)

12.11 Ballast cleaner

The main tasks of the ballast bed can be defined as follows [292]:

- uniform distribution of the wheelset forces on the subgrade;
- reduction of dynamic stress, caused by dynamic axle loading;
- ability to be maintained and to hold the vertical position achieved during maintenance;
- assurance of the horizontal stability (lateral resistance to displacement).

Figure 12.57 shows, that on polluted ballast, the load distribution function of the ballast bed and the full drainage function of the subgrade must be restored by undercutting-cleaning. The general rule is:

- ballast cleaning becomes appropriate when there are more than 30% of fines of less than 22 mm size in the ballast [63].
- ballast cleaning is absolutely necessary when there is more than 40% pollution.

Blanketing machine with ballast rehabilitation

Manual insertion of sand blankets is not only costly, also the compactness and uniformity of the blanket cannot be maintained. Insertion of blankets by road construction equipment needs to close down the track during the rehabilitation process and again in many cases the quality of the finished product is questionable. Different machines and machine systems are available, which can insert sand blankets, geosynthetics or other protection layers under the track, in track possessions, without the necessity to dismantle the track.

The AHM 800 R is a formation rehabilitation machine which uses re-cycled ballast for the formation protective layer (Figure 12.61). The AHM 800 R has two independent excavation devices. The smaller front excavating chain picks up the top layer of the old ballast bed (20 to 25 cm). The material is freed of small metal parts then an impact crusher breaks the ballast stones to a size of 0 to 35 mm. The crushed ballast is mixed with water plus additional FPL material in a mixing plant and prepared for installation.The second, larger excavation unit removes the remaining old ballast and the top layer of the old subgrade. Earth compactors smooth the remaining surface. If required, a geotextile or a fabric layer can be rolled over this or styrofoam slabs or geogrids can be laid (Figure 12.62 and Figure 12.63).

Figure 12.61: Formation rehabilitation machine AHM 800 R

13 NUMERICAL OPTIMIZATION OF RAILWAY TRACK

13.1 Introduction

Designing is a complex process that includes several stages starting with making sketches and ending with a ready to use product. In each stage of the designing process a number of decisions are to be made, so that designing can be considered a decision making process. In this chapter we will show how mathematical methods such as numerical optimization can help in a decision making process.

The design process commences with defining the requirements of a product. This means that a design has to perform a certain task and has to satisfy certain criteria. Using modern numerical methods, such as e.g. finite element method, the complex behaviour of a design under various loading situations can be simulated. Such simulations can help to estimate the performance of a design and, moreover, reduce the number of expensive prototypes and laboratory tests. Tremendous progress in computer technology has enormously increased the possibilities to numerically simulate complex systems. Modern numerical models used for analysis of static and dynamic behaviour of a railway track have been discussed in the previous chapters.

When the static and dynamic behaviour of the design has been analysed, the next step is to optimise it. Design optimization generally means improving the system's performance during the working cycles while keeping a number of manufacturing, operational, and failure conditions as well as cost limitations in mind. For example, to optimise a railway track one can think of reducing noise produced by a moving train, improving passengers' comfort, or reducing maintenance costs.

In the case of traditional design of technical systems optimization is carried out in a primitive way by modifying design parameters and repeated numerical analyses. The modifications are mostly based on the designer's experience and possibly also on information about the sensitivity of the system's performance to changes in the design parameters. However, it is a time consuming process and, moreover, success cannot be guaranteed.

The most systematic way to improve the design is to use numerical optimization techniques. Combined with advanced numerical simulation analysis, these techniques search for an optimal design based on which possible prototypes can be built. In the forthcoming section a theory and application of structural optimization of railway engineering will be presented. Starting with a brief introduction to numerical optimization, some practical aspects of using an optimization theory will be discussed in Section 13.2.

All optimazation problems have been solved using a modern optimization technique called Multipoint Approximations based on the Response Surface fitting (MARS) method which is briefly discussed in Section 13.3.

Then, three railway engineering applications are presented in Section 13.4 and further. The first one deals with optimization of embedded rail structure. The other two applications are so-called inverse problems in which an optimization technique is used to determine some of the system's parameters. One problem concerns determining ballast lateral resistance parameters based on measurements obtained using a tamping machine. Another problem deals with identifying the dynamic properties of the elastic compound of an embedded rail structure using an hammer excitation test.

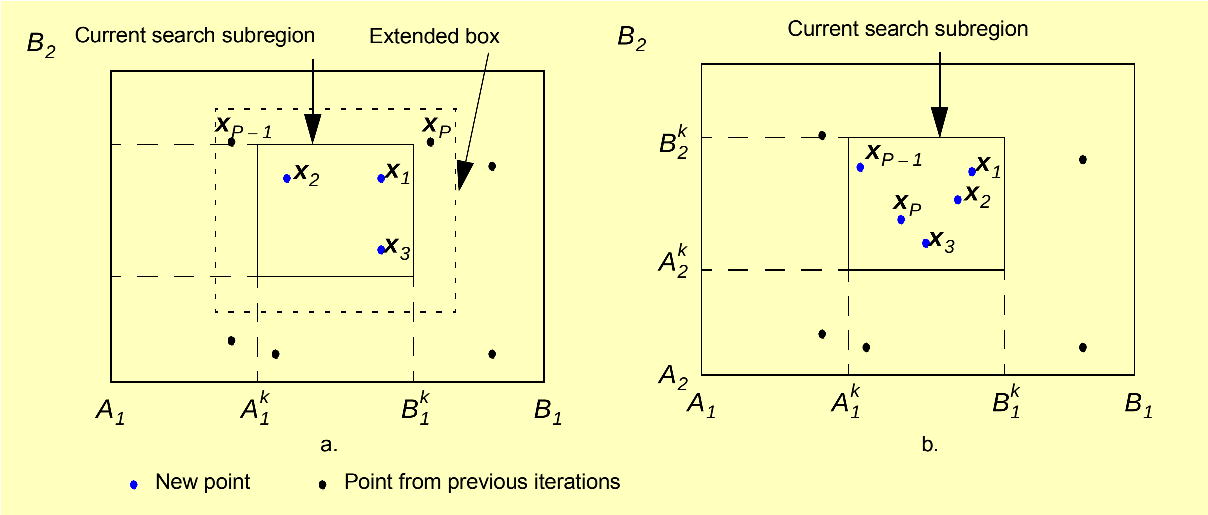


Figure 13.2: Extended (a) and random plan of experiments in MARS method

– It has to contain a number of tuning parameters to be defined using the general (non-linear) least-squares method;

– It must be simple enough to be used in numerous repeated calculations;

– It should not contain a considerable level of numerical noise in order to not cause convergence problems in the optimization process.

Simple yet quite efficient approximations are intrinsically linear (with respect to the tuning parameters) models, namely linear and multiplicative models:

$$\tilde{F}(\mathbf{x}, \mathbf{a}) = a_0 + \sum_{i=1}^{P} a_i x_i \quad \text{and} \quad \tilde{F}(\mathbf{x}, \mathbf{a}) = a_0 \prod_{i=1}^{P} (x_i)^{a_i} . \tag{13.11}$$

These models have been successfully applied to various design optimization problems [173], [175], [178]. For details on approximations using the MARS method we refer to [173].

The obtained approximation functions are used in the formulation of the optimization problem (13.6)-(13.8). In order to solve this problem any conventional method of non-linear mathematical problem can be used. In MARS a Sequential Quadratic Programming (SQP) method has been chosen [229]. The solution of the problem is considered a starting point for the next iteration. The move limits are changed depending on the quality of approximation and location of the optimal solution in the previous step. The main rules of the strategy to change the move limits employed in MARS are:

– If the approximating functions do not adequately represent the original ones in the current optimum point, which means that the search subregion is larger than the range of applicability of the current approximations, the move limits (13.8) are changed to reduce the size of the search subregion;

– If the approximations are good and the solution to the optimization problem (13.6)-(13.7) is an internal point of the search subregion, which means it could be considered as an approximation of the solution of the original optimization problem (13.2)-(13.4), the search subregion is reduced;

– If the current optimum point belongs to the boundary of the search subregion (at least one of the move limits is active) and the approximations are good, the size of the subregion is not changed for the next iteration.

Numerical models

Here the response quantities relating to cost efficiency, acoustic properties, and maintenance effort are considered of importance to the optimum performance of ERS. To estimate the performance of an ERS design, static and dynamic models have been developed. The static response quantities such as stresses and displacements of an embedded rail structure under various loading conditions have been obtained using a general purpose finite element package ANSYS**.**

The 2-D and 3-D FE models of ERS are shown in Figure 13.5. Before these models were included in the optimization process, they were verified by comparing the results of laboratory tests and finite element calculations [175].

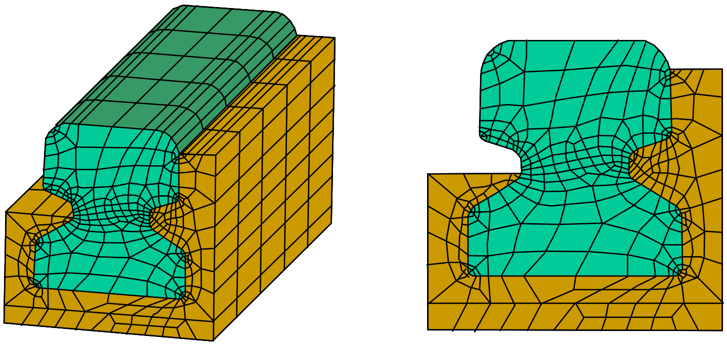


Figure 13.5: 3-D (a) and 2-D (b) finite element models of ERS with SA42 rail

It should be noted that the elastic strip under the rail, which is a common part of existing designs, is now replaced by elastic compound. In [175] it is demonstrated that the same behaviour of a structure can be achieved by only using a compound with adjusted E modulus and Poisson ratio.

Three loading cases have been considered to obtain the static response quantities of a structure for assessment of ERS design (Figure 13.8). The dynamic responses of ERS have been obtained using a finite element program RAIL that is described in Section 6.9. The numerical mode of ERS, built using RAIL, is shown in Figure 13.6. Here, the application of RAIL focuses on two aspects, namely acoustic noise produced by a track and wheel-rail wear.

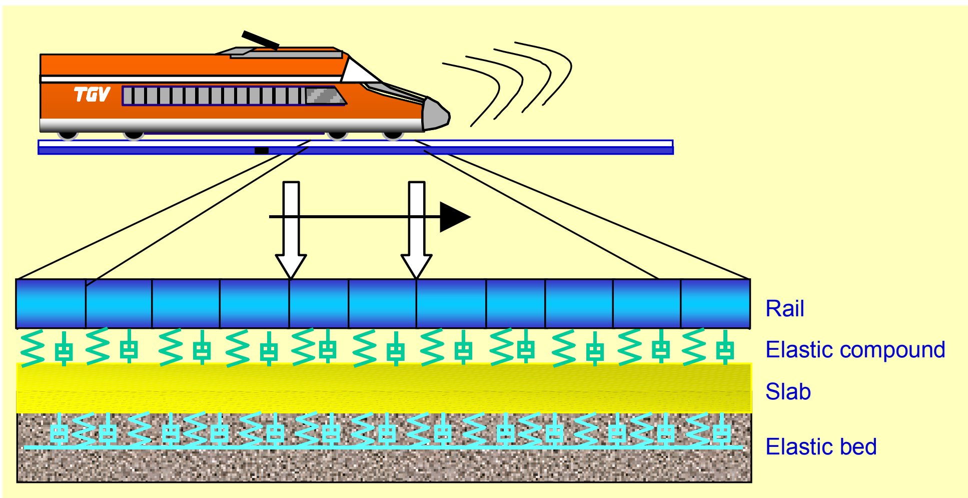


Figure 13.6: RAIL model of ERS (moving train loading case)

In order to ensure that the static and dynamic models describe the behaviour of the same ERS, they have been coupled to each other by adjusting geometrical properties such as cross-sectional moment of inertia, etc. of the rails in the dynamic analysis based on the parameters of the static model. Also, the static and dynamic vertical stiffness of ERS has been correlated. To determine the static stiffness of a track the vertical load has been applied at the top of the rail head as shown in Figure 13.8a. The static (K_{stat}) and dynamic (K_{dyn}) vertical stiffness are then calculated as $K_{stat} = F_y/u_{y,1}$ and $K_{dyn} = 2K_{stat}$ ($u_{y,1}$ is the vertical displacement of the rail corresponding to this loading case).

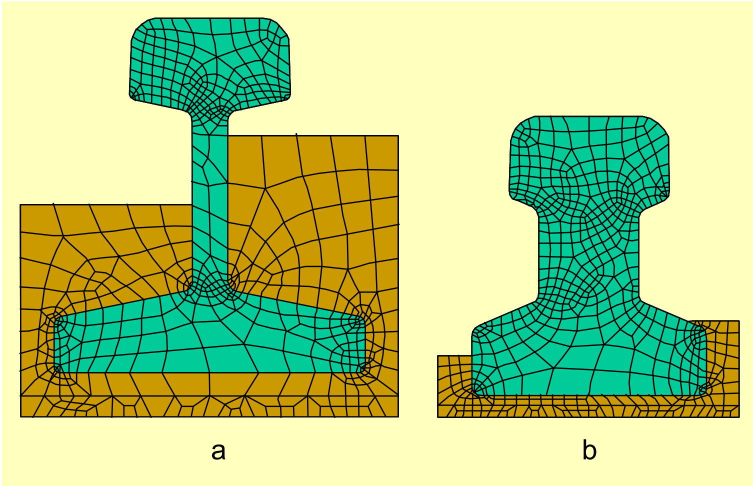


Figure 13.11: Initial design of ERS with conventional rail (a) and result of multi criteria optimization with equal preference (b)

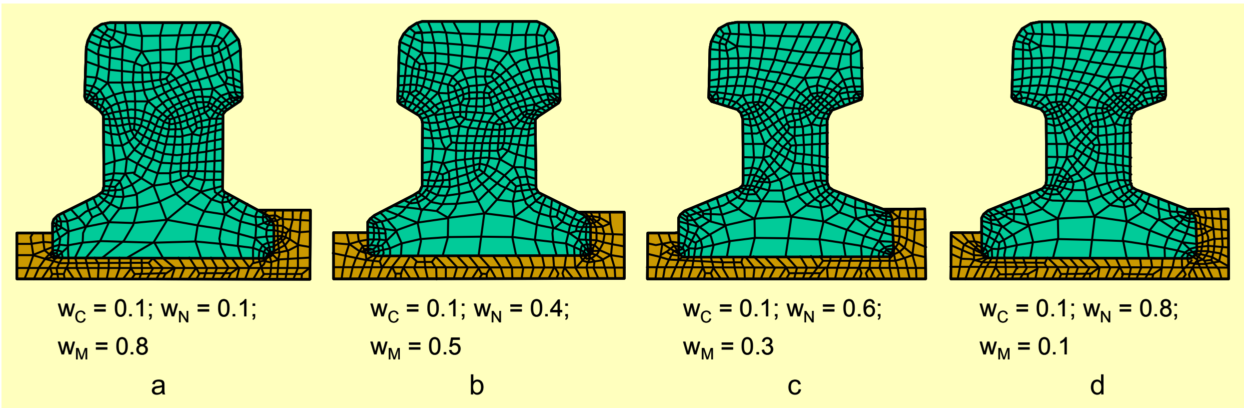


Figure 13.12: Geometrical results of multi criteria optimization, variation of preferences for noise (W_N) and maintenance (W_M)

Figure 13.12 shows the results of optimization problems with varied preference factors related to the reduction of the maintenance effort and the noise (see Table 13.3) while considering the cost objective less important (the corresponding preference coefficient is constant $w_C = 0.1$). The numerical results collected in Table 13.3 clearly reflect the effect of the chosen preferences for the optimum design. From this Table it can be seen that the stiffness of compound and resonant frequency of ERS increase (from 5.39 MPa to 9.25 and from 290 Hz to 380 Hz respectively) as the noise objective becomes more important (w_N increases from 0.1 to 0.8). On the other hand, the contact forces increase as well (from 11.2 kN to 13.8 kN) as the maintenance becomes less important (w_M decreases from 0.8 to 0.1). From Figure 13.12 one can see the tendency of the rail shape of the optimum design to change as the maintenance objective becomes less important (from a to d). It should also be noted that the only difference between the two last designs (c and d) is the thickness of the compound layer under the rail (see Table 13.3).

In another sequence of optimization problems, the preference factor for the noise objective was constant $w_N = 0.1$ while the preferences for the other two objectives were varied. The ERS shape results from optimization are given in Figure 13.13 and the numerical results are collected in Table 13.3. Again the stiffness of compound (and therefore the vertical stiffness of the structure) increases as the reduction of maintenance becomes less important (w_M reduces).

a b

Figure 13.26: Hammer Excitation Test on classical track (a) and Embedded Rail Structure (b)

by means of Fast Fourier Transform (FFT) into Frequency Response Functions (FRF), while assuming the linear behaviour of a track.

The inertance frequency response function $H_{AF}[kg^{-1}]$ relates the applied force (input) F and the recorded accelerations of a track (output) A and reads:

$$H_{AF}(f) = \frac{S_{AF}(f)}{S_{FF}(f)} \qquad (13.26)$$

in which

$S_{AF}[mN/s]$ is the complex cross-spectrum of accelerations (output);

$S_{FF}[N^2s]$ is the power spectrum of the impulse force (input);

$f[Hz]$ is the frequency.

Sometimes, it is also important to analyse the receptance frequency response function $H_{XF}[m/N]$. Similar to the inertance, it relates the applied force (input) F and the resulting displacement (output) X as:

$$H_{XF}(f) = \frac{S_{XF}(f)}{S_{FF}(f)} = \frac{1}{(2\pi f)^2}\frac{S_{AF}(f)}{S_{FF}(f)}, \quad S_{XF}(f) = (2\pi f)^{-2}S_{AF}(f) \qquad (13.27)$$

in which $S_{XF}[mNs]$ is the complex cross-spectrum of displacements (output). From (13.26) and (13.27) the following relation between the inertance and receptance FRF can be obtained:

$$H_{AF}(f) = (2\pi f)^2 H_{XF}(f) \qquad (13.28)$$

One of the advantages of FRF is that it is not sensitive to the magnitude and duration of an impulse load. Moreover, in [169] it is shown that the recording signals obtained using different types of hammers are very close, except the extremely low and extremely high frequencies which are not considered here.

13.6.3 Numerical model

In order to better understand and interpret measurement results, a numerical model that is able to describe the various kinds of behaviour of a railway track is necessary. The choice of parameters for such a model is crucial for the assessment and prediction of track performance. Once determined on

14 TESTING AND ACCEPTANCE

14.1 Introduction

Railway track is composed out of many different components which have already been introduced in Chapter 5, Chapter 8, and Chapter 9. All components have very specific functions and are designed to fulfil their functions in the best possible way and for the longest possible period of time.
Product development in railway engineering has been highly influenced by empirism and conservatism; a consequence of the prevailing safety requirements, low costs for labour and materials, and availability. During the last decades, techniques have rapidly been developed which allow the production of components according to better specifications and higher quality standards. New materials, mechanisation, automation, production as well as test devices have been introduced and used in railway practice.

Besides the component properties which can be controlled during the manufacturing process, the system properties of the assembled track structures should be controlled as well and should meet quality standards. This puts emphasis on the quality control of construction and maintenance activities carried out by contractors.

This chapter will focus on recent developments in component and structural testing, quality assessment of track components, and structures leading to acceptance. The owner of the track will then be enabled to provide the train operator with safe, durable, and cost-efficient infrastructure.

Figure 14.1: New developments in railway track require testing before acceptance

14.2 Component testing and acceptance

14.2.1 Mechanical properties

Track components are supposed to have specific mechanical properties that enable the track to support and guide railway vehicles. In Table 14.1 a number of track components and properties are listed. These properties are arbitrarily categorised and show their most important features. Mechanical properties are not necessarily the most important ones, but they reflect the principle of considering the track as a mechanical system subjected to vehicle loading.

	Elasticity	Strength	Stability	Durability
Rail profile		X		X
Fastening system	X		X	X
Sleepers		X	X	X
Ballast	X		X	X
Slabs		X		X
Track support systems	X		X	X

Table 14.1: Overview of the most important track properties of each component

14.2.4 Stability properties

Track stability guarantees correct track positioning even under severe loading conditions. The most interesting reason why track requires sufficient stability is that it will buckle due to high longitudinal forces in the rails. To overcome this, the framework of rails and sleepers should be sufficiently rigid and embedded in a stabilised ballast bed. Rigidity in the framework is achieved by means of longitudinal and torsional resistance in the fasteners. In [29] tests are listed to determine these resistances. Longitudinal resistance in assembled tracks varies between 8 and 20 kN per rail (per set of fasteners). The torsional resistance of most of the present fasteners is between 30 and 70 kNm/rad [282] and between 100 and 250 kNm/rad per meter of an assembled track framework.

In order to conserve the fixation between rail and sleeper in ballasted track, the longitudinal resistance should be at least 12 kN. Lower or extremely low resistance values are applied in case of interaction with civil structures like bridges. Track stability should then be provided in alternative ways. Lower longitudinal resistance also applies for slab tracks in which case stability of the track framework is almost guaranteed. In [46] a minimum longitudinal resistance of 5 kN per rail (per set of fasteners) is required. In Figure 14.9 a test is shown for determining the longitudinal resistance of a specific embedded rail section in slab track (see Section 9.8), while in Figure 14.10 a test set-up is shown for standard fastening systems mounted on a sleeper.

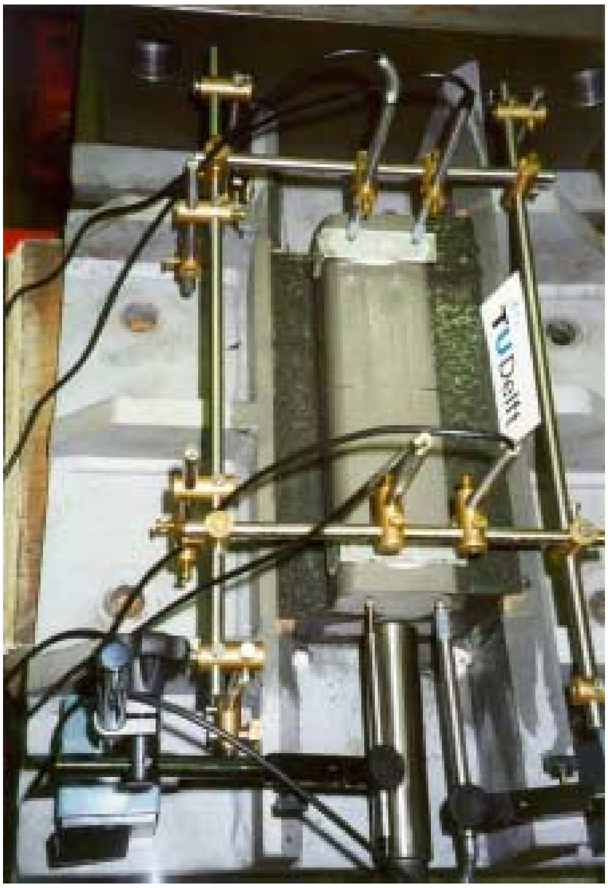


Figure 14.9: Longitudinal resistance test of an embedded rail section

Figure 14.10: Longitudinal resistance test of a fastening system mounted on sleeper

The properties of ballast beds regarding stability have been investigated by many, both theoretically and empirically, in the field and in laboratories. In [282] the results of lateral stability of a ballast bed are reported as a function of vertical track loading and longitudinal forces. Lateral ballast resistance should be determined for track panels instead of single sleepers, as the co-operation of neighbouring sleepers is not negligible. Lateral track resistance in ballast is divided into elastic stiffness and plastic friction.

Figure 14.24: Recording properties of embedded rail test sample in laboratory

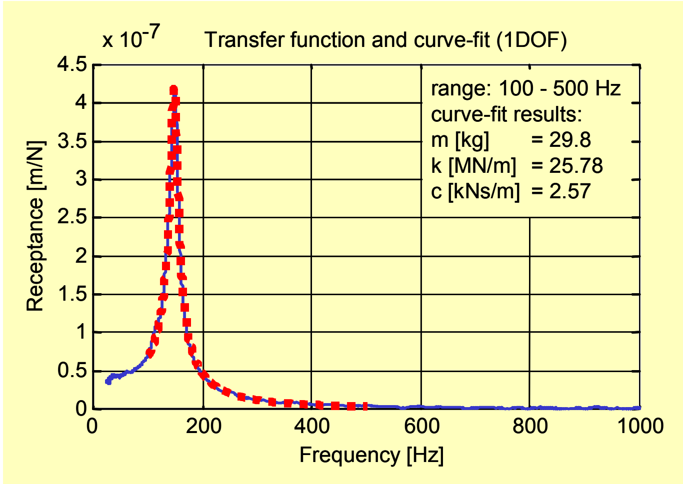


Figure 14.25: Extracting embedded rail dynamic properties by means of curve-fitting of the recorded transfer function

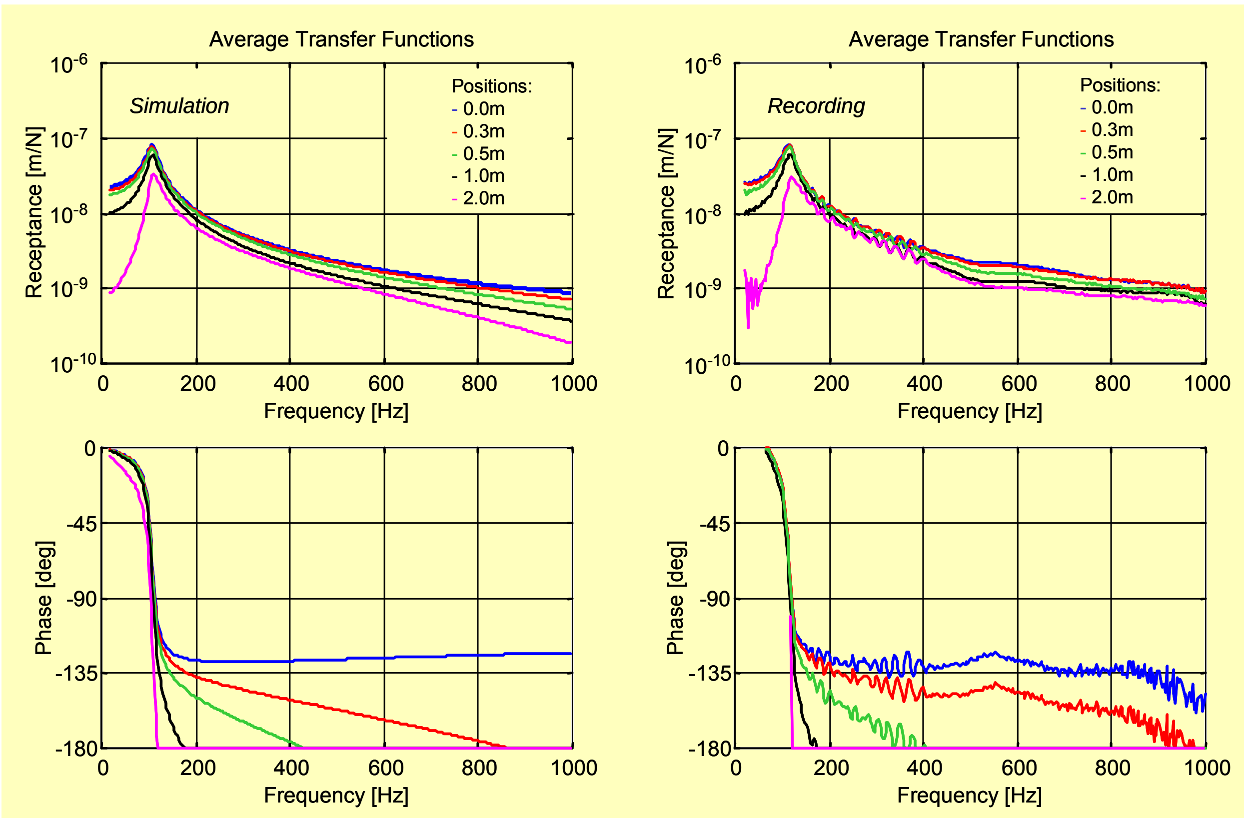


Figure 14.26: (a) Simulated and recorded transfer functions of embedded rail structure at rail head

The assessment of track dynamics with well defined track geometry, vehicle, and operational data is illustrative for comparing track alternatives. For instance, in [172] and Chapter 13 the track dynamics are assessed by means of the standard deviation in wheel-rail interaction forces calculated with the finite element model of an embedded rail structure. The track dynamics were changed repetitively in an optimization procedure, while the track geometry, vehicle, and operational data were kept constant. Due to several other criteria and objectives, the optimum design with respect to track dynamics has not been found yet. For quality assessment of track structures, the transfer function should fit into bandwidth diagrams which, however, depend on predefined quality levels [232].

15 NOISE AND VIBRATION

15.1 Introduction

In recent years, rail transport systems have increasingly received complaints from people living alongside lines and above underground lines. The disturbance is usually caused by the direct emission of noise or vibration from the railway, but sometimes noise in buildings is produced by the walls vibrating which is referred to as re-radiated noise.

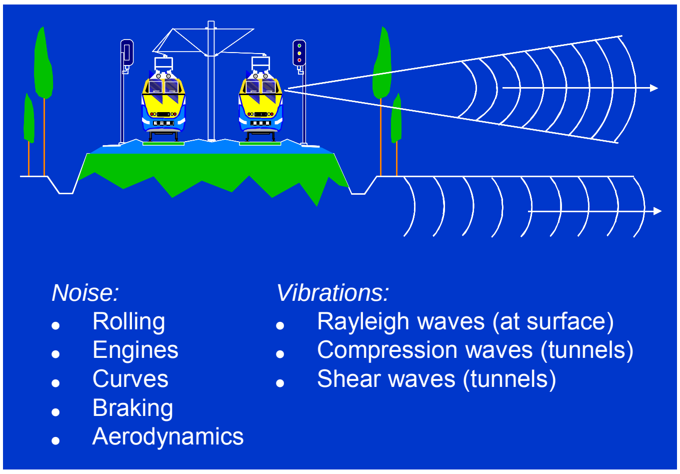


Figure 15.1: Noise and vibration radiation principle

Vibrations and structure-borne noise mainly occur at lower frequencies below 50 Hz. At higher frequencies these vibrations attenuate increasingly rapidly. The energy at higher frequencies is radiated as noise mainly through the wheels and the rails. Roughly speaking, vibrations and structure-borne noise occur in the frequency range 0 - 100 Hz and noise between 30 - 2000 Hz. The principle of noise and vibration radiation is illustrated in Figure 15.1.

15.2 Some definitions

As the dynamic range of the spectral values is rather large, they are mostly represented on a logarithmic scale expressed in dB, according to:

$$L[dB] = 20 \log \frac{p_1}{p_2} \tag{15.1}$$

Figure 15.2 shows the relationship between the linear scale and the dB scale.

Power spectral values are mostly calculated as root mean square (rms), or effective value, per 1/3 octave band. In the low frequencies associated with vibrations, accelerations are often integrated to produce velocities.

When expressing them as dB values a reference value should be given. Noise values are normally expressed relatively to a reference value 2 10^{-5} N/m^2.

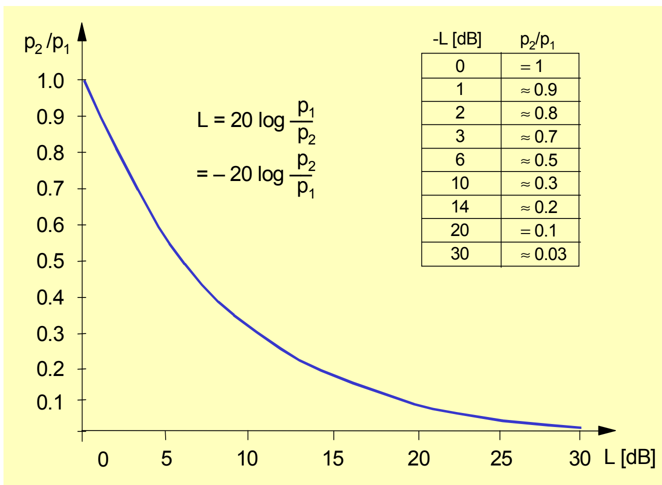


Figure 15.2: Relationship between dB scale and linear scale

The human perception of noise is characterised by the filter shown in Figure 15.3. This A-filter, as it is referred to, removes almost all contributions below 200 Hz. Noise levels are normally presented after having been A-weighted. This is indicated in dB(A). Depending on the application, spectra can either be presented as A-weighted or not.

Silent steel bridges

The noise radiation on bridges has lead to various developments to reduce the nuisence. The main sources are the wheels, the rails and the steel bridge girders. In The Netherlands the track specific solutions were primarily found in the application of embedded rail. Here, in the first place, the rail is to a large extend cast into Corkelast and therefore the radiation surface is relatively small. Figure 15.19 shows an example of the more traditional embedded rail concept on steel bridges.

Figure 15.19: Traditional embedded rail concept on steel bridge

A more sophisticated solution is the concept depicted in Figure 15.20, representing an integrated design. The principle is based on supporting the rail structure by a very stiff spring, comprised of the main girder of the bridge, with an intermediate flexible spring consisting of corkelast between girder and rail.

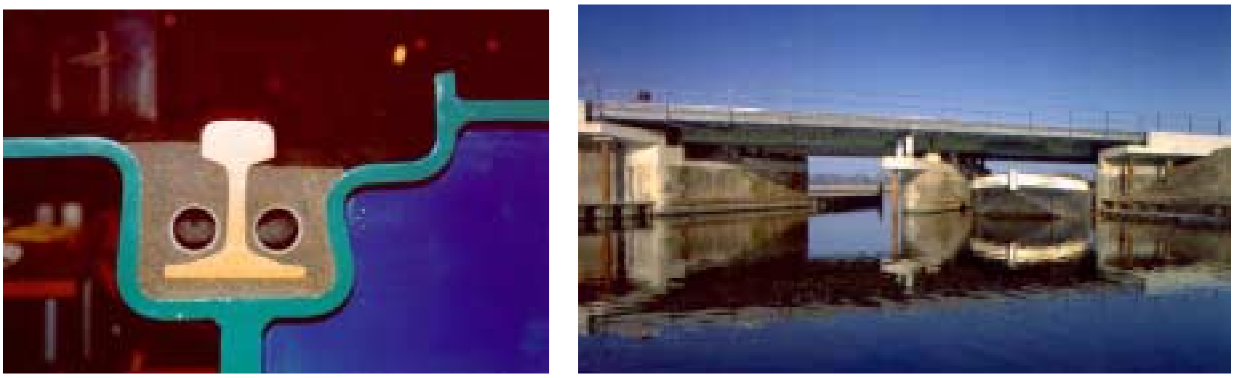


Figure 15.20: Silent bridge cross section and view of a bridge

As the rail trough forms a monolithic part of the main girder a very stiff support is created with an extremely low vibration level due to the dynamic decoupling between rail and bridge. Figure 15.21 shows a measuring example of a silent bridge and simultaniously presents the noise level spectrum of a conventional steel bridge. The difference is in the order of 10 dB.

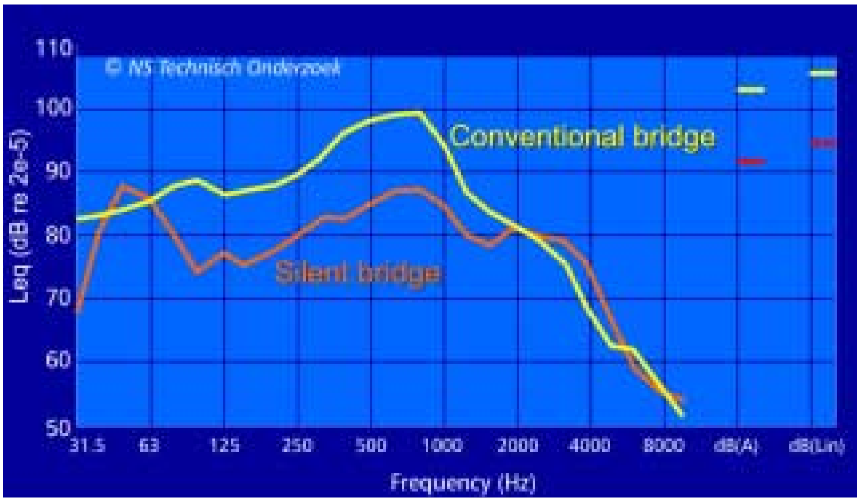


Figure 15.21: Measured noise energy levels at silent bridge and at conventional bridge

16 INSPECTION AND DETECTION SYSTEMS

16.1 Railway Infrastructure Monitoring

Railway Infrastructure Monitoring (RIM) represents one of the most important parts of an Asset Management System (AMS). For more details on this subject please refer to Chapter 19. The overall managing capabilities of the AMS will greatly depend on the quality of the available monitoring systems. As the focus of this book is the railway track, track monitoring and condition assessment techniques will be given special consideration. However, since it was stressed that successful track condition analysis and consequent management could only be performed in combination with other railway infrastructure, monitoring of other infrastructure objects and means for their management will also be briefly elaborated on. Special consideration will be given to substructure monitoring and the monitoring of switches and crossings, as their influence on the track condition is significant.

The reason for monitoring is usually twofold. The first, immediate reason is obviously to detect irregularities that could endanger the safety and reliability of railway traffic. However, if a monitoring technique is continuous and fast enough to allow consecutive monitoring runs to be performed at regular time intervals, an extremely important temporal aspect is obtained which is of essential importance to a successful condition-based management. This means, that such a monitoring technique could provide insight into the infrastructure element's behaviour over time. And this could allow condition forecasting and consequent maintenance planning. This concept usually represents the ultimate goal of any condition monitoring.

16.2 Tunnel monitoring

Continuous tunnel monitoring represents one of the latest developments within the field of railway infrastructure management. Only recently, techniques for laser, thermal, and video scanning of the tunnel’s inner surface became available and more widely used. Many railway tunnels worldwide are more than a 100 years old, and due to the extensive development above or adjacent to existing services there has been an increased emphasis on monitoring the integrity of tunnels.

Figure 16.1 shows the tunnel profile laser/visual/thermal scan processing system "ScanView". ScanView is a viewing utility which uses sophisticated data manipulation to display the information gathered by the TS 360 BP Scanner in a straightforward and intuitive manner. Amongst its features are:

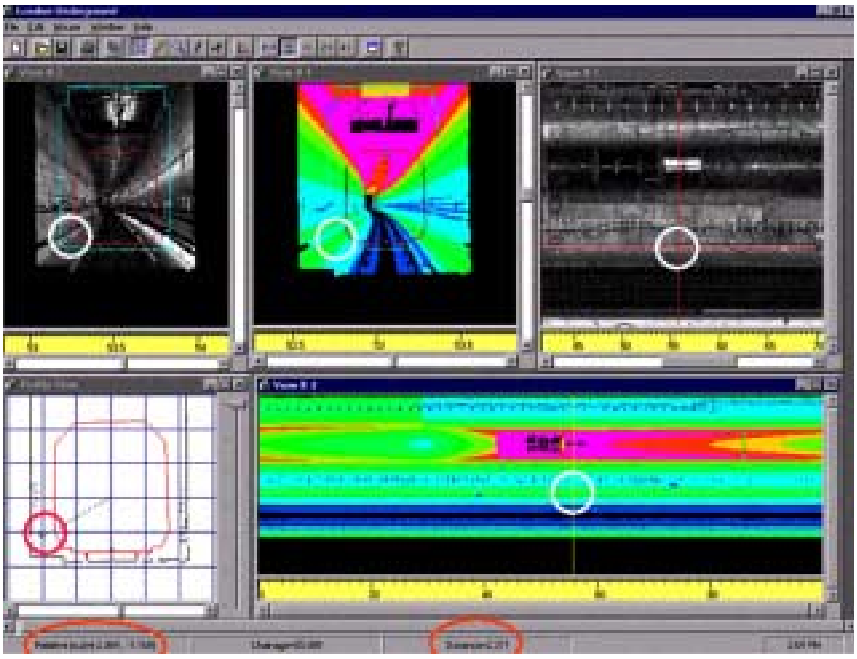


Figure 16.1: Tunnel profile laser/visual/thermal scan processing system - Scan View

– Plan viewing of visual, thermal, or profile data;

– Cross-section display for any chainage of the scan;

– Accurate real life distance measurements between features on the scan;

– Reconstruction of the three dimensional image viewed from any chainage;

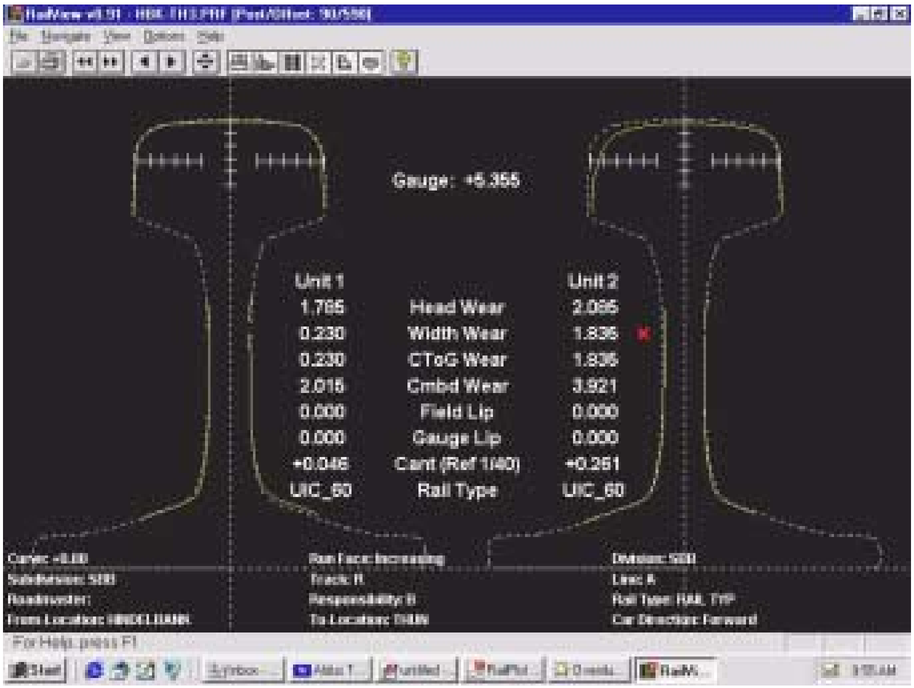


Figure 16.49: Real-time diagram of the rail cross-section

Rail surface

The exact data for planning rail grinding is acquired using special corrugation measuring cars of the company Speno. Track recording cars can be equipped with axle box acceleration measuring devices which give a good indication of the location of the errors. In some cases they are also equipped with precise corrugation measuring devices.

16.7.4 Overhead wire recording

To evaluate the geometry of the contact wire it is necessary to measure the height of the contact wire above the rails and the horizontal position of the contact wire and to know the relative position between track and overhead wire. It is, therefore, practical to have the catenary measuring units on the track recording car.

The non-contact laser measuring device, shown in Figure 16.50, is a very compact and precise device which is mounted on the roof of the measuring vehicle and can easily be integrated into a track recording car. In addition, a measuring pantograph for measuring dynamic reaction forces should be available.

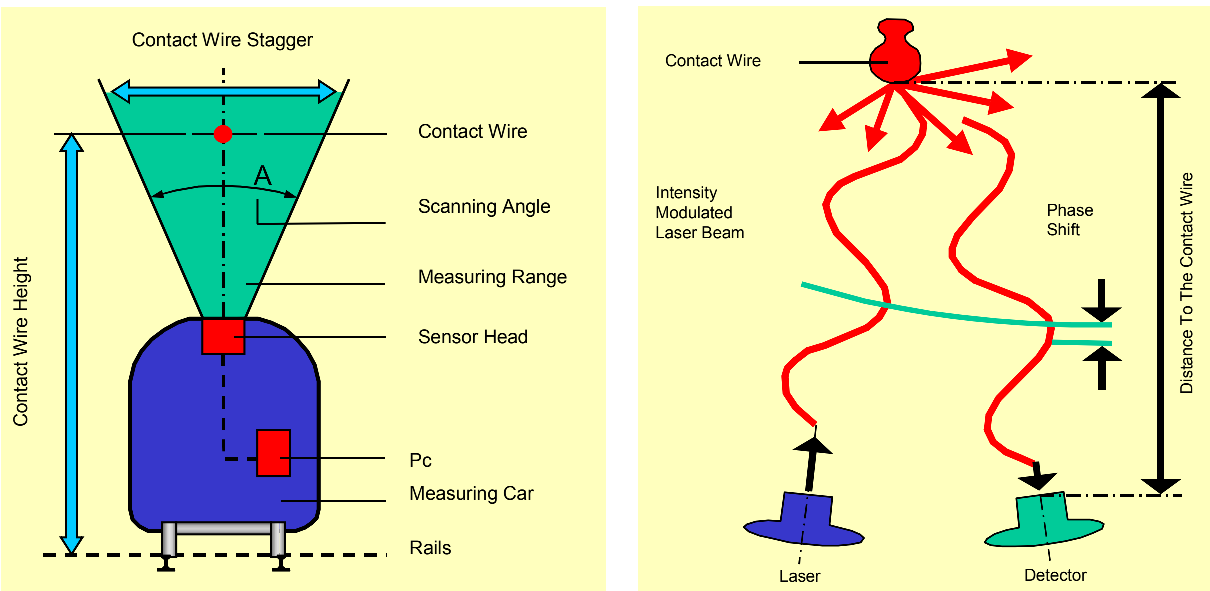


Figure 16.50: Overhead wire measuring system of Plasser & Theurer

16.7.7 Track recording cars

High speed track recording cars

Track recording cars for speeds of 200 km/hr and more are usually standard railway coaches equipped with non-contact recording systems. One of the most advanced cars is the EM 250 of Austrian Railways ÖBB (Figure 16.51 and Figure 16.52). The basic vehicle is a four axle RIC passenger coach with Minden-Deutz 524 bogies which is pressure tight and air conditioned.

Figure 16.51: High speed track recording coach EM 250 of ÖBB

For level and alignment, the basic measuring unit is the Applanix strap down inertial measuring platform backed up by a laser gauge measuring unit. The geographical position of the coach and the assignment of the measuring data to the line position is organised with a GPS unit.

Rail profiles are checked with an Orian system. In addition, ÖBB has developed a program to evaluate the equivalent conicity of defined vehicles in relation to the recorded track.

That car has, furthermore, force measuring bearings for vertical and lateral wheel forces and video cameras on both ends.

The track data is analysed on board with the ÖBB/ADA 2 analysing system and all measuring data is submitted to the ÖBB data base by means of wireless LAN stations.

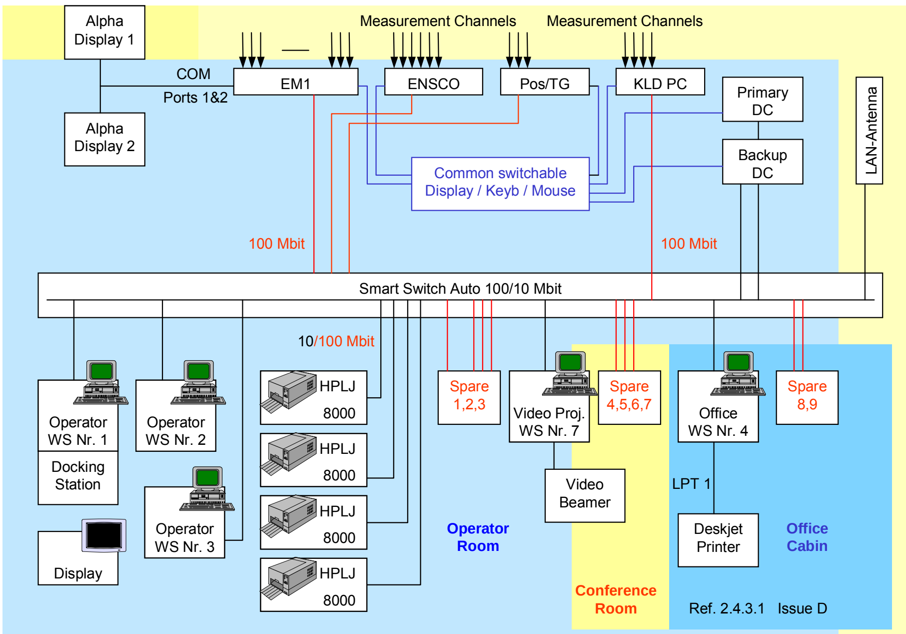


Figure 16.52: Data flow of EM 250

Recording cars for standard speeds

For standard networks recording cars with measuring speeds varying between 80 to 160 km/hr are used. Some of them are towed cars, but the majority are self propelled units. The measuring systems which are used are non-contact as well as telescopic measuring axles.

– *UFM 120 on Netherlands railways*

Since 1999, tracks in the Netherlands are recorded with the UFM 120 of the company Eurailscout (Figure 16.53). This self-propelled non-contact measuring car for 120 km/hr recording speed is equipped with the same measuring equipment as the EM 250 of ÖBB for track and rail measurements. In addition, it has a video rail defect scanning system, a non-contact laser measuring unit for the overhead wires, and a video catenary inspection system.

– *EM 130 on Belgium railways*

Also since 1999, a self-propelled four axle measuring car with 130 km/h measuring speed is used to measure the TGV tracks and standard tracks in Belgium (Figure 16.54). The track measuring system is a chord measuring system based on telescopic measuring axles and measuring bogies. This is an example of the coexistence of both measuring systems in the field of modern track measurement.

For rail profile and overhead wires non-contact laser measuring systems are used.

Figure 16.53: Track recording car UFM 120

Figure 16.54: Track recording car EM 130 of SNCB

Figure 16.55: Track recording car EM 130 of SNCB

Recording cars for smaller networks

The majority of measuring cars for smaller networks, like urban transport systems and local networks, are self-propelled two axle vehicles with telescopic measuring axles (Figure 16.55). Measuring speeds vary between 30 to 80 km/hr, sometimes up to 120 km/hr. The measuring parameters can be the same as described for the other measuring cars.

During integration, small off-sets of the accelerometers will also be integrated and this will soon lead to inadmissibly large errors. Non-linearities produce the same effects. These problems are also avoided by high-pass filtering.

In principle, it might be possible to place an acceleration transducer vertically above the wheel, rigidly connected to the axle box, and in this way obtain the vertical rail position. In practice, this solution is not possible as the high accelerations require a wide transducer measuring range. Small amplitudes at long wavelengths, however, only produce very low accelerations which, again on account of non-linearities, cannot be measured in this manner.

The accelerations are therefore measured at a point on the coach. As they are considerably lower, a more sensitive transducer can be used. At the same time the relative vertical displacement of the acceleration transducer in relation to the axle box is measured using displacement transducers. The track position can be derived from these parameters.

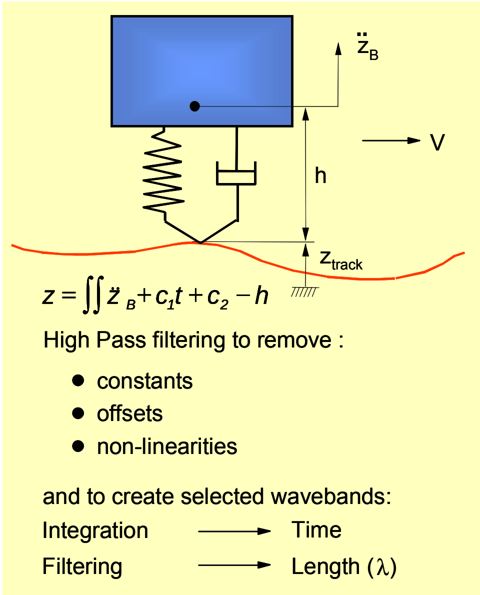


Figure 16.77: Principle of an inertial measuring system

Thus, here the coach and its suspension perform the function of a mechanical low-pass filter. The high frequencies, which cause the high accelerations, are filtered before they reach the acceleration transducer.

It will be clear that those wavelengths of the track which, at a certain running speed, produce frequencies lower than the natural frequency of the coach, are principally determined by means of the acceleration transducer, whereas the shorter wavelengths, which produce frequencies higher than the natural frequency of the coach, are principally determined by the relative displacement measurement. Of course, no phase differences are allowed between signals which are to be combined.

In The Netherlands the following track geometry signals are produced: cant, level, alignment, and gauge in the 0.5 - 25 m and 0.5 - 70 m wavebands, while the quasi-static component in the 70-∞ m waveband is also determined for cant, curvature, and gauge. Moreover, the track twist is calculated from the difference in cant on the two bases of 6 m and 2.75 m.

16.10.3 Dynamic signals

Vertical

How the dynamic measurements are actually carried out is shown diagrammatically in Figure 16.78 and will be explained using the example of vertical level. The measured vehicle body acceleration is doubly integrated with respect to time in order to obtain the absolute spatial car body displacement. For reasons explained previously, the long waves are cut off electronically at 70 m (attenuated by 3 dB) using a fourth-order Butterworth filter. The purpose-built electronic control system continuously adjusts the time-defined parameters of the Butterworth filter to the speed, so that the characteristic, based either on spatial frequency or on wavelength, is not altered. As the system integrates three times at the most, high-pass filtering should be performed with a filter at least one order higher to eliminate the effect of drifting due to the integration of offsets.

As the accelerometer is mounted rigidly on the floor of the car body, the acceleration is always recorded perpendicular to the floor. In actual fact, though, it is the vertical acceleration which is involved. This is derived from the measured signal by making an electronic correction as a function of the car body rotation due to cant.

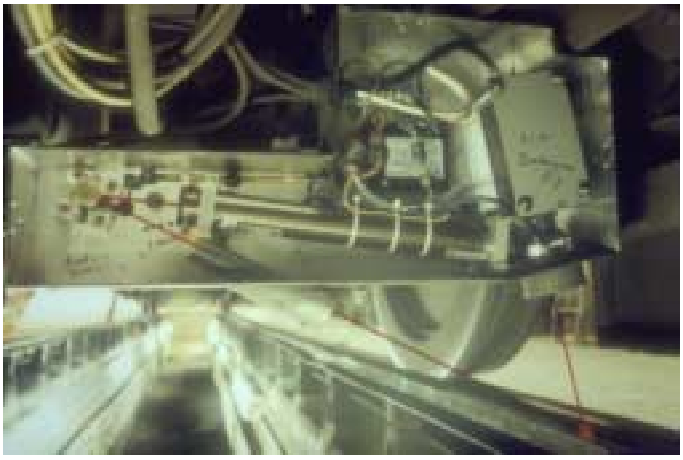


Figure 16.81: Laser system mounted in measuring bogie

The mounting frame is provided with an aluminium cover with rubber gaskets for sealing and has two openings which are protected by nozzles. The camera "looks out" through one of the openings and the laser beam exits via the other. A third opening admits filtered air under pressure at a rate of approximately 100 m^3/h. As this air exits through the other openings at considerable speed, it prevents dirt and dust from entering through these openings.

The cameras are on the bogie frame and are directed at an angle of 1: 5 to the gauge face of the rail head at the point where the light-spot is located. The cameras are equipped with an array of 256 photodiodes, providing a measuring range of 50 mm. The light falling on a diode is integrated for about 1 ms.

Signal processing partly takes place in the hardware and partly by a microprocessor. The latter determines the sliding average of the last 8 scans.

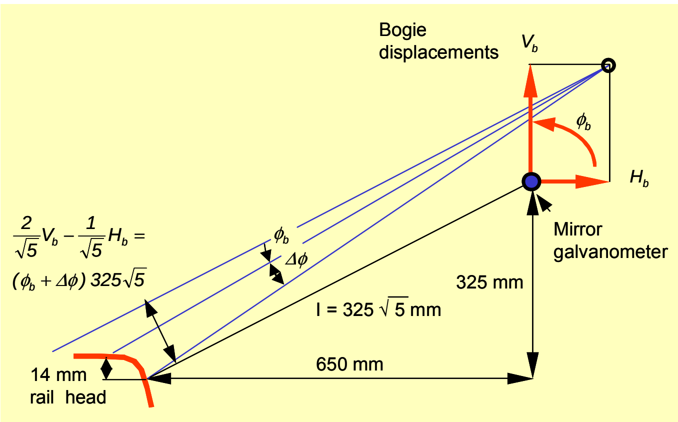


Figure 16.82: Principle of galvo control to position laser spot on rail head

The laser spots are kept at the correct level of 14 mm below the rail head by controlling the current through the mirror galvanometer. The galvanometers have a natural frequency of about 1500 Hz and are critically damped. To control the galvo angle, the bogie displacements relative to the track are used as depicted in Figure 16.82. For a vertical displacement V_b, a horizontal displacement H_b, and a rotation ϕ_b the galvo angle should be corrected by:

$$\Delta\phi = -\phi_b - \frac{H_b}{\ell\sqrt{5}} + \frac{V_b}{\frac{1}{2}\ell\sqrt{5}} \qquad (16.5)$$

in which $\ell = 325\sqrt{5}$ mm.

Figure 16.83: Transducer for vertical displacement between axle and bogie frame

The lateral bogie displacement is obtained from the camera output. Vertical bogie displacement and bogie rotation are determined by means of 4 linear displacement transducers, as shown in Figure 16.83, which have been mounted between bogie frame and axle.

16.10.4Quasi-static signals

In addition to the dynamic signals, quasi-static signals are produced for cant, curvature, and gauge. The measuring principles are presented schematically in Figure 16.84. Problems due to drift and lack of initial conditions mean that the quasi-static cant is not determined by integration of the rate gyro signal, but by making use of the lateral car body acceleration, curvature, and recording speed as indicated in Figure 16.84.

Equivalent standard deviation values with respect to NS' BMS system, produced by the recording cars of various administrations, were published in [88] and are summarized in Table 16.7

Network	NS	DB	CFF	SNCF/ SJ	CSD	BR	FS	CFR	PKP
Level	1	1.24	0.91	0.91	1.52	1.14	1.33	1.40	0.73
Alignment	1	1.41	1.44	1.47	1.77	1.20	1.72	1.95	–

Table 16.7: Conversion table for track recording car output

16.12.3 Track geometry spectra

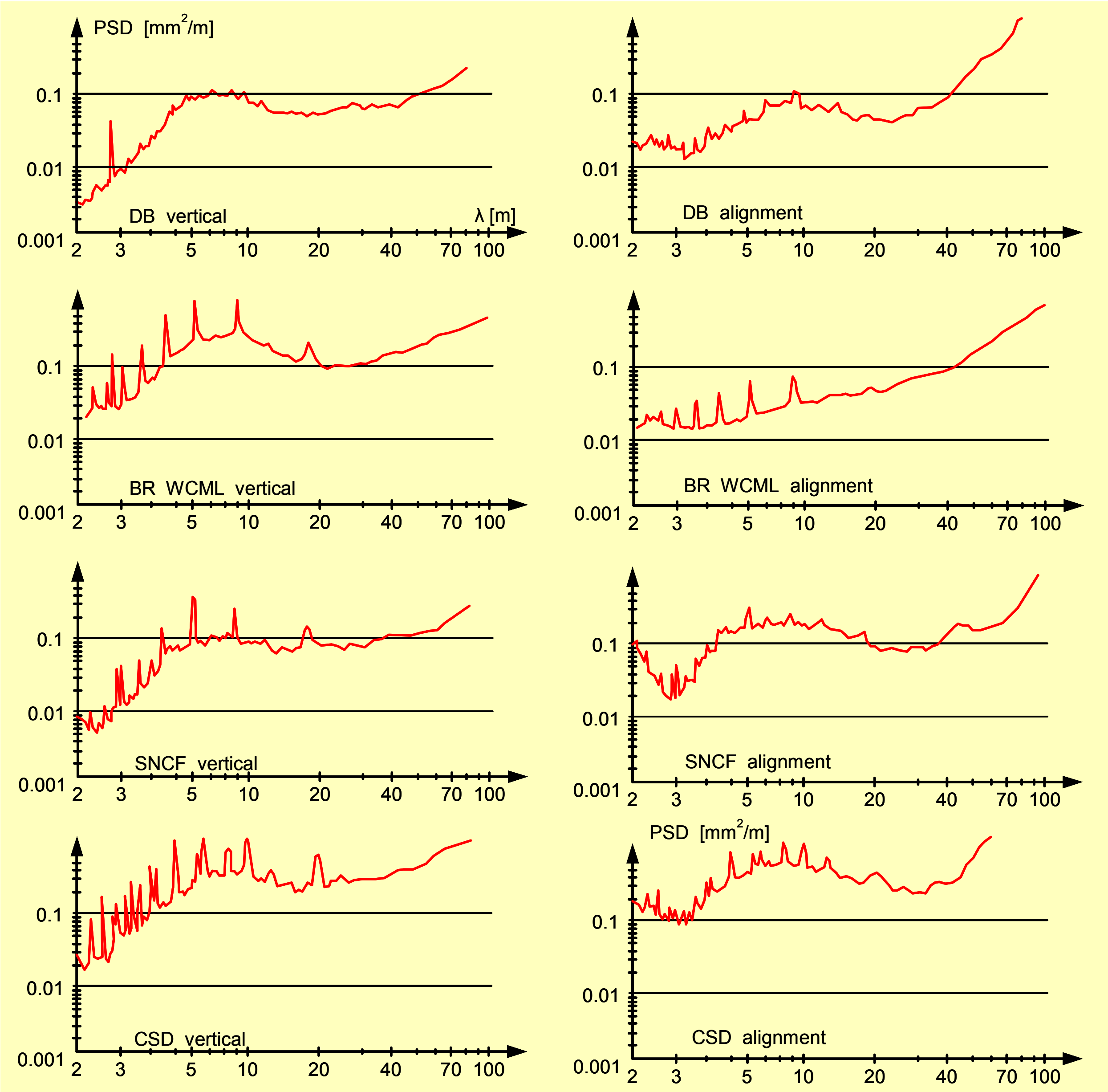


Figure 16.101: Psd-functions for vertical track geometry based on BMS measurements carried out for ORE D 161

A more detailed way of looking at track quality is by means of power spectral density functions, which show how the variance or energy of a signal is distributed over the wavelengths. The theory of how these functions can be determined is treated in Chapter 6.

17 HIGH-SPEED TRACKS

17.1 Introduction

17.1.1 Vehicle reactions

Despite vehicle running stability, wheel/rail forces and car body accelerations at high speeds should be confined to acceptable limits. As far as the track is concerned, these vehicle reactions can be influenced by the track geometry. In addition to the quasi-static components, which occur in curves, the response components comprise a dynamic part. The dynamic components can be further split up into low frequency steady-state contributions and high frequency impact loads occurring locally at welds and generated by wheel flats.

On account of the quasi-static and low frequency loads, the track may not displace permanently in the lateral direction, i.e. the Prud'homme criterion should be met. To guarantee safety against derailment, the Y/Q ratio should be less than a specific value, normally 1.2. For the sum of the quasi-static and low frequency Q-force, i.e. the 97.5% value, DB apply a standard of 170 kN. According to [252], BR calculations use 340 kN for the sum of the quasi-static, low frequency, and high frequency Q-force. In the case of the TGV, a maximum Q-force of 137 kN was attained for the quasi-static Q-force supplemented by twice the standard deviation of the low frequency dynamic component [231]. This 67% value of the Q-force is practically the same as the value applied to the German ICE.

As far as passenger comfort is concerned, the quasi-static and low frequency dynamic car body accelerations are dominant. In extreme cases a non-compensated lateral acceleration of 1.5 m/s^2 is allowed. For both the TGV and the ICE the absolute maximum for the total peak value of the car body acceleration is set at 2.5 m/s^2. Under normal conditions the standard deviation of the car body accelerations will be limited to 0.2 m/s^2.

In the case of the various high-speed projects, extensive series of measurements have been performed to check that the limits discussed earlier are not exceeded. A summary of the DB measurements on wheel/rail forces, published in [147], was discussed in Chapter 4. The 97.5% value of the Q-force attributable to locomotives appears to increase up to 150 kN at 250 km/h. Freight wagons with 22.5 t axle loads exert the same Q-force on straight track at 120 km/h. According to [231], during measurements on TGV trains a 67% value of the Q-force of 134 kN was found.

In [27] measurements on the German ICE are described. Figure 17.1 shows the ΣY_{2m} forces as a function of speed, measured in a curve with R = 3400 m and in a curve with R = 495 m and a cant deficiency of 140 mm. In all cases the Prud'homme criterion was met. No acceleration at car body level was found that exceeded 2.5 m/s^2.

In order to test the viability of the system periodic acceleration measurements should be carried out. The safety limits according to the SNCF are set as follows:

Transverse bogie acceleration	6 m/s^2	
Transverse body acceleration	2.5 m/s^2	v < 350 km/h
Vertical body acceleration	3 m/s^2	

Table 17.1: Safety limits for high-speed operation

The above values are absolute safety criteria. Under normal conditions the values of Table 17.2 should not be exceeded. With the opening of new lines these values are used during the so-called homologation runs in which the speed is step wise increased until the maximum line speed plus 10 % is achieved. These measurements are periodically repeated. If the values of Table 17.1 are exceeded the SNCF should report this to the Ministry of Transport.

speeds up to 300 km/h. The measured track geometry serves as input based on which, with the aid of transfer functions, the response values are calculated in the frequency domain.

The relevant wavebands to be covered by the recording system have already been discussed in previous sections. They are summarized in Table 17.9 together with the measuring accuracy required if they are to be reproducible. This accuracy is expressed in terms of standard deviation for dynamic signals and amplitude for quasi-static signals and peak values.

17.2 The Korean High Speed Railway Project

17.2.1 Introduction

Figure 17.3: Seoul-Pusan High Speed Line

The Korean High Speed Line between Seoul and Pusan is linking the major economic and cultural centers of Korea. The line has intermediate stations at Chonan, Taejon, Taegu and Kyongju, and consists of 412 km double track, including 112 km (27%) of at-grade sections, 109 km (27%) of viaducts and 191 km (46%) of tunnels (Figure 17.3). The train sets are based on TGV technology. The commercial speed will be 300 km/h and the travelling time 1hr 56 minutes between the two terminal stations. The daily transport of passengers is estimated 520,000. The annual tonnage amounts to about 60 MGT.

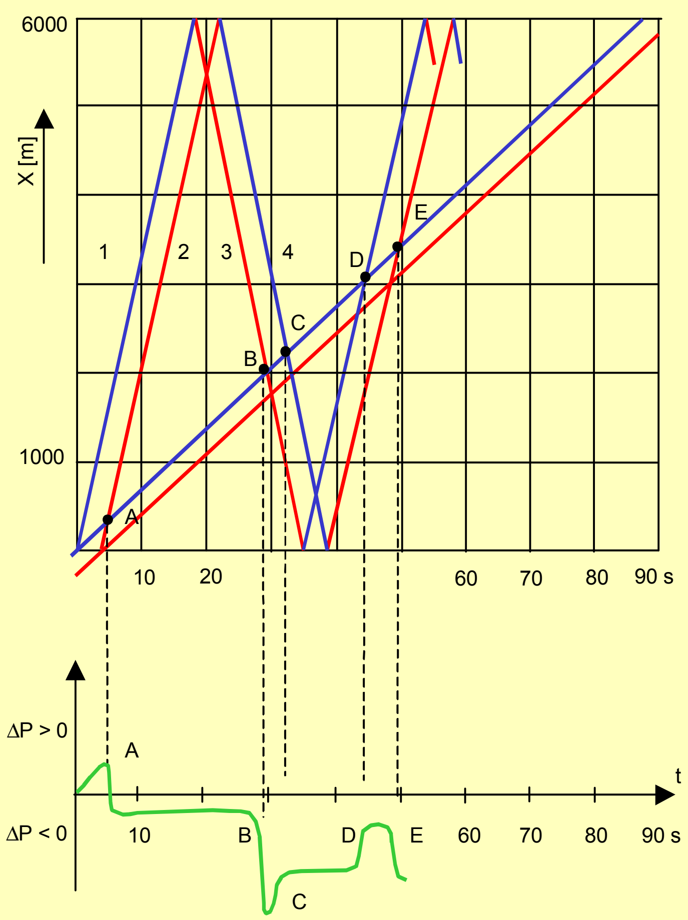
To cut down the initial investment, the construction of the first phase of the high-speed line terminates in Taegu, while in the interim the upgrading and electrification of the existing conventional line between Taegu and Pusan will allow the revenue service starting in April 2004. Construction of the Taegu–Pusan section via Kyongju as well as underground stations in Taejon and Taegu comprise phase two, which is scheduled for completion in 2010.

In March 1992 construction was started of a 57.2 km long double track test section located between Chonan and Taejon on which test runs at 300 km/h commenced in December 1999.

17.2.2 Civil Works

One of the main features of the project is the large number of the civil structures. Standardized structures and construction methods have been adopted to optimize the construction processes. Typical viaduct structures comprise two or three continuous 25 m spans or two 40m continuous spans. The application of those typical spans limited the length between bridge deck expansion joints to less than 80 meters, thus avoiding the installation of rail expansion joints in most instances.

The Precast Span Method (PSM) was adopted for the bridge deck construction of several long viaducts. This method was state of the art construction technology, which involved the prefabrication, transport and installation of 25 m long Precast PC Box Girders. The 600-ton girders are cast in a temporary casting yard located near one end of the bridge, and transported on specially designed carriers to the point of installation. The concrete box girders are lifted from the carrier and moved along a launching beam. The launching beam is supported at the front end on the pier head, on which the girder is to be installed, and at the rear end on the previously installed girder.



Line 1: compression wave (blue line) caused by the front of the train when entering the tunnel

Line 2: depression wave caused when the rear of the train is entering the tunnel

Line 3: position of the front of the train in the tunnel

Line 4: position of the rear of the train in the tunnel (red line)

Figure 17.11: Wave forms in tunnel

Figure 17.11 shows the characteristics of the air pressure in tunnel (external pressure) and train (internal pressure) in case of a sealed train and a standard train. In a sealed train the internal pressure differences are much lower than in the standard train. The differential values are in the order of some kPa, being a few percent of the atmospheric pressure.

Line (1) gives the position of the compression wave (front) caused when the train entered the tunnel. This compression wave propagates with the sound speed (340 m/s) to the end of the tunnel and is then reflected as a depression wave (red line (3)).

Line (2) shows the position of the depression wave (front) caused when the rear of the train entered the tunnel. This depression wave also propagates with the sound speed (340 m/s) to the end of the tunnel and is then reflected as a compression wave (red line (2)).

These waves move between the tunnel ends while a train is passing through the tunnel. The points A to E show the position and time where the train front negotiates the compression and depression waves.

During the train passage in a tunnel the alternating air pressure waves may resonate, which may cause great changes in air pressure. Measurements have shown values of 7.5 kPa. The tunnel length and cross section, the train dimensions and speed determine the external air pressures on the train. The air tightness of the train determines how the external air-pressures are transformed into internal air-pressure variations causing passenger discomfort.

17.3.4 Basic design criteria for tunnels

There are four main criteria for tunnel design:

- Passenger comfort in the train at line speed;
- Passenger safety if the exterior of the train is open by any reason;
- Safety of maintenance personal in tunnels;
- Strength of the train exterior.

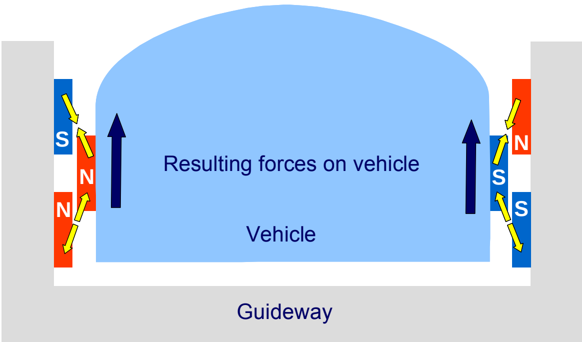


Figure 17.18: Levitation principle

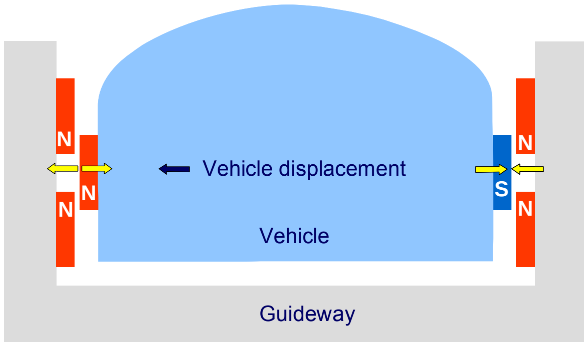


Figure 17.19: Lateral positioning principle

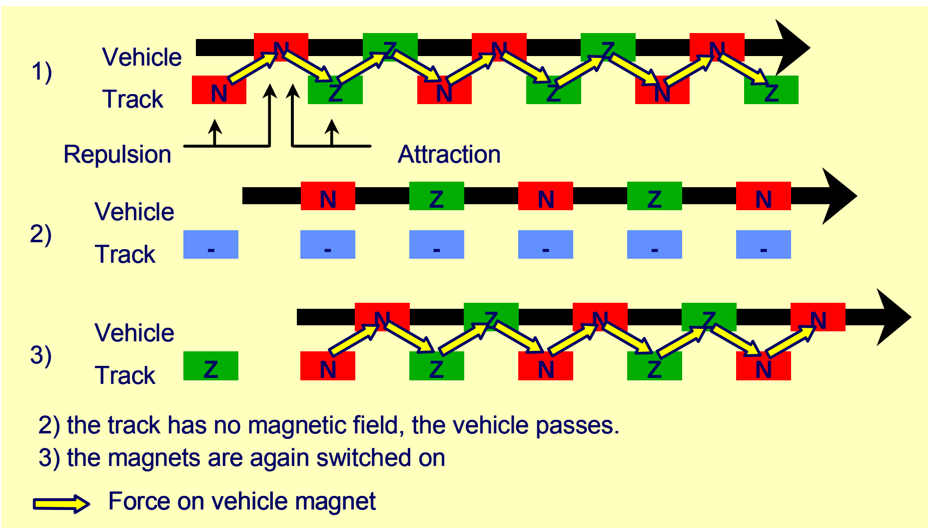
For the lateral guidance levitation coils facing each other are connected under the guideway, constituting a loop. When a running vehicle displaces laterally an electric current is induced in the loop, resulting in a repulsive force acting on the levitation coils of the side near the car and an attractive force acting on the levitation coils of the side further apart from the car. Thus, a running car is always pushed to the center of the guideway as shown in Figure 17.19.

The propulsion principle is explained in Figure 17.20. A repulsive force and an attractive force, induced between the magnets, are used to propel the vehicle via the superconducting magnet. The propulsion coils located on the sidewalls on both sides of the guideway are energized by a three-phase alternating current from a substation, creating a alternating magnetic field on the guideway. The on-board superconducting magnets are attracted and pushed by the shifting field, propelling the vehicle.

The guideway consists of a permanent way structure provided with ground coils corresponding to the conventional motor, as displayed in Figure 17.21. This is a vital element of maglev. For the Yamanashi Maglev Test Line three methods of installing the ground coils for propulsion, levitation, and guiding to the guideway were adopted.

In the beam method, the sidewall portion was constituted solely of concrete beams. The entire process from beam manufacturing to installation of the ground coils take place at the on-site factory. A finished beam is transported to the work site within the guideway, to be placed on two concrete beds set up in advance there.

Figure 17.20: Propulsion principle



18 TRACK MAINTENANCE MANAGEMENT SYSTEMS

18.1 Introduction

In order to meet competition from other modes of transport, there is an increasing demand upon the railways to improve reliability, efficiency, and transit times. The resulting requirements for improvements in speed and axle load mean that the demands made upon the track are becoming more onerous. In order to provide cost-effective track to meet this need in the future, it is essential to be able to improve the methods by which the performance of the track is monitored and to have reliable methods for prediction and planning.

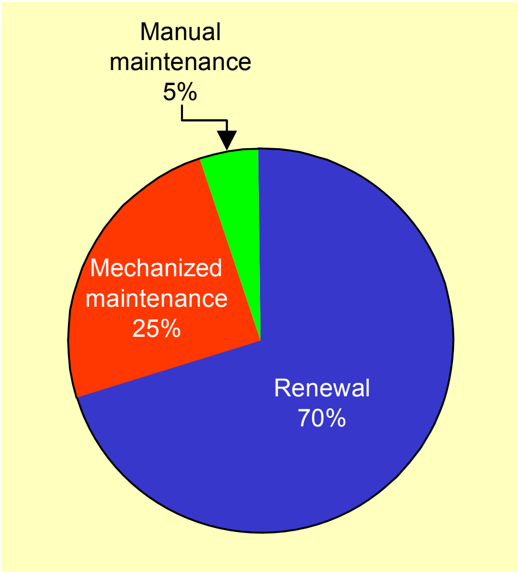


Figure 18.1: Total annual expenditure for maintenance and renewal at NS (price level 2000)

Maintenance and renewal of large railway networks require huge amounts of money. For example, the annual expenditure for NS permanent way (price level 2000) amounts to about EUR (€) 180 million (Figure 18.1). Only 25 % of this value concerns mechanised track maintenance and 5 % manual track maintenance. It is, therefore, obvious that the high expenses are caused by track renewal. To achieve an effective cost reduction the decision makers need to be provided with adequate information. With objective data of this sort, processes become more transparent and, thus, can be better controlled.

As will be explained in more detail in Chapter 16, computer-aided Track Maintenance Management Systems (TMMS) logically represent a constitutive part of Asset Management Systems (AMS). However, until AMS become sufficiently developed and fully accepted as a concept, TMMS will exist more as isolated systems. Even as isolated system, if designed properly, they represent invaluable tools for any track and/or infrastructure manager.

In order to properly manage track maintenance, a vast amount of data is needed. Types of data to be collected for computer-aided TMMS are summarised in Figure 18.2. For an efficient analysis of the track the data had to be divided into segments. In fact, all information is linked through the track segment to which it refers.

This information is by no means restricted to just data from automatic recording systems. Other data, such as from visual inspections, various layout and operating data, data about speed reductions, spot

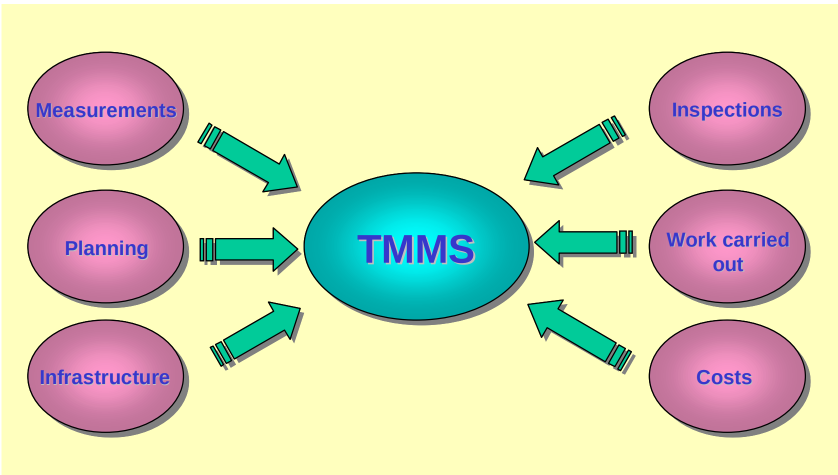


Figure 18.2: Types of data to be collected for computer-aided Track Maintenance Management Systems

18.8.3 System functions and process

To cover the functions of the planners or the manager, the structural arrangement of the EOCTRACK system is divided into five principal application functions, one for each level, providing an increasingly detailed view of the functional model, see Figure 18.9.

Level 1 - Initial diagnosis
M&R works needs per track component. For each segment of track, the system, based on the decision rules, undertakes a fully automatic diagnostic procedure and displays the basic requirements for the additional data required for the more detailed diagnosis of track segments needing M&R works.

Level 2 - Detailed diagnosis
This level is based on the additional data that the user should have provided and additional decision rules. This part of the procedure is interactive. The outcome is a "Preliminary M&R Work Plan".

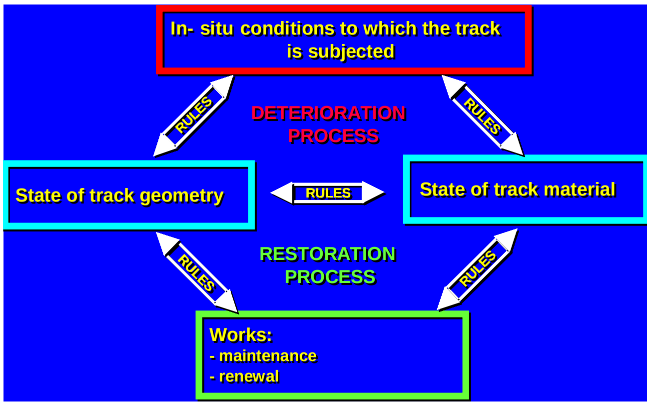


Figure 18.8: ECOTRACK Rules

Level 3 - Coherence of the elementary M&R works

The works necessary according to Level 2 are subjected to a fully automatic coherence analysis based on decision rules. Works are evaluated in the sense that the works of the same type are combined together if they were planned close enough, both in time and in space, Figure 18.10. Also, renewal works of different types planned on the same track section and close in time are grouped together, e.g. sleeper & fastening renewal and ballast cleaning/renewal, or sleeper & fastening renewal and rail renewal, or rail renewal and ballast cleaning/renewal. The result is a final M&R Work Plan proposition (see Figure 18.11).

Level 4 - Optimization of resource allocation
This level is based on an interactive man-machine process. It estimates the cost plan and optimises the selected track M&R works in long-term planning. Costs of continuous and spot maintenance and renewal works are included. The user chooses the best alternative in accordance with the railway's M&R practice.

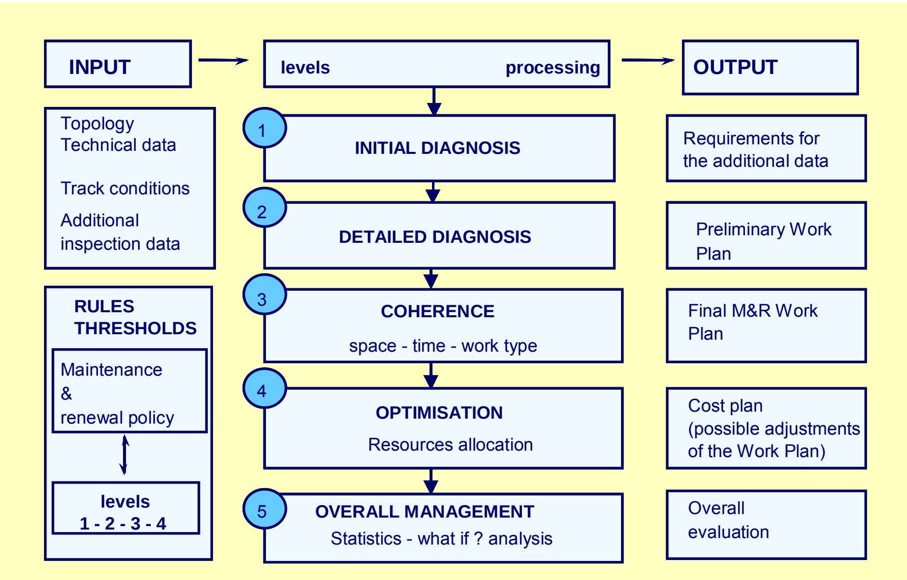


Figure 18.9: ECOTRACK - Functional Process

19 RAILWAY ASSET MANAGEMENT SYSTEMS

The last two decades of the twentieth century have seen the emergence of computer-aided track maintenance and renewal systems based ever-increasing amount of data. Problems of inaccessibility regarding the required data, especially the data in the digital format suitable for the automatic analyses, which were present during the eighties, were largely overcome during the nineties. This has enabled much better and reliable track condition analyses, and prompted the development of comprehensive condition-based decision support systems for track maintenance and renewal, such as ECOTRACK.

On the other hand, the development of systems like ECOTRACK necessitated further development of more sophisticated and more reliable track deterioration models. This, along with the constantly rising amount of high-quality track condition data available, made it clear that track condition and related maintenance and renewal management could no longer be considered separately from other railway infrastructure elements. Instead, it became obvious that track management had to be coupled to substructure management, track structure management, overhead lines management, etc.

The reasons for that were numerous. Firstly, it was long known that the other railway infrastructure elements, like substructure for example, had very significant influence on the track superstructure behaviour. This was especially true at the locations where persistent and recurring problems with track geometry were observed. However, until the high-quality data were made sufficiently available and until systems like ECOTRACK emerged, this could never be sufficiently quantified. The reason for that was that only by using these systems it would become possible to overlay many different kinds of track condition information at the same time, thereby enabling the condition evaluations to be made for many aspects.

The lack of reliable, efficient, and cost-effective methods for continous and repetitive substructure monitoring additionally hampered the problem. Secondly, ever increasing need and strict regulations regarding track availability, both of which becoming increasingly pronounced during the nineties, made the joint management of all railway infrastructure absolutely necessary. These two reasons, along with the always present strive for higher efficiency and cost reduction, have initiated the appearance of a new management concept, which was usually referred to as Asset Management or Asset Management System (AMS).

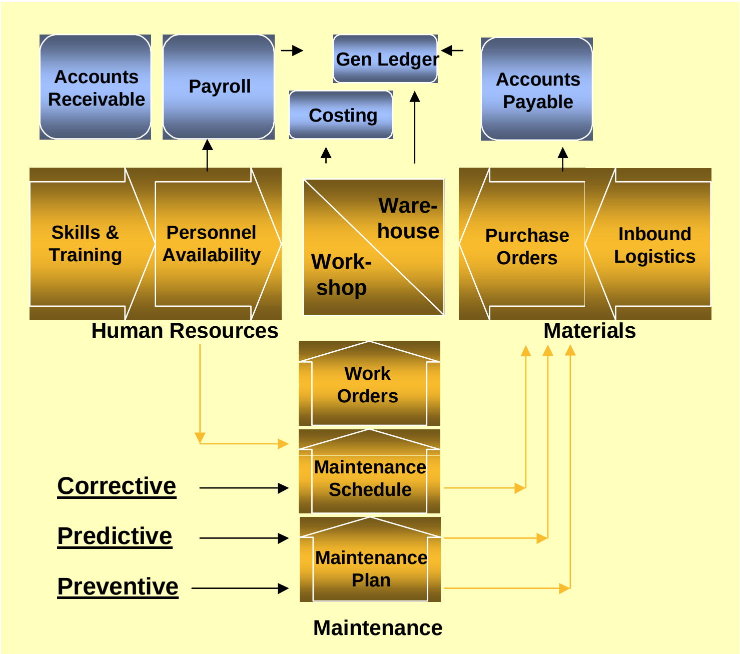


Figure 19.1: Core Elements of an AMS

This method allows for fast and relatively inexpensive collection of the infrastructure location information. Aerial-photo images which have been regularly collected over the years in almost every country as a part of standard surveying procedures sustain this. The accuracy of this method currently ranges between 10 and 20 cm. However, for the purposes requiring higher accuracy, other methods could prove to be more appropriate.

19.3.2 Method using laser, video and GPS technology

In this case, a helicopter is used with a colour video system and a laser scanning system. A laser system, installed on the helicopter platform, which accurate co-ordinates have been defined using GPS devices, is capable of collecting data from 8000 geo-referenced surface points at typical speeds of about 75 km/h [56].

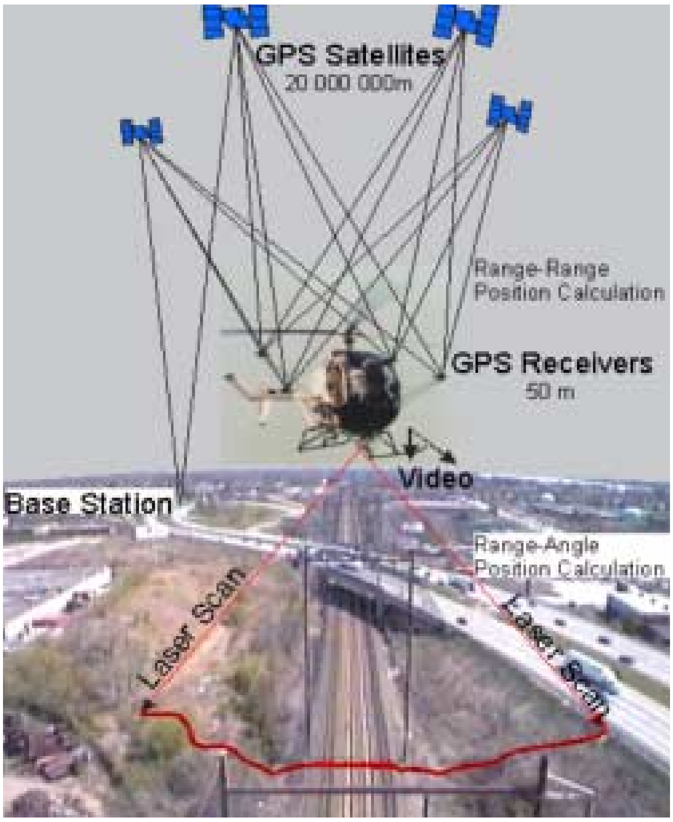


Figure 19.3: Graphical Presentation of FLI-MAP Data Collection System

A FLI-MAP system currently used in the USA and South Africa can be seen in Figure 19.3. A helicopter is equipped with four GPS receivers called Rover Receivers, mounted as indicated in Figure 19.3, and a certain number of GPS receivers are positioned along the flight path. A satellite to helicopter range to range calculation called on-the-fly Kinematic GPS is used to position the helicopter over the railroad right of way.

These calculations provide a precise GPS platform position attitude from which laser ranges and imagery data are collected. From the GPS referenced platform, a custom-designed, eye-safe, reflectorless range finder laser is used to measure first return ranges from 20 to 200 meters above the ground surface. Every scan has a width of 60 degrees and contains 200 range measurements. Each scan record contains timing, laser attitude, laser range and intensity, and data verification/error detection information.

Operationally, the laser scans at a rate of 40 times per second and has a coverage width that is approximately equal to the flying height above ground. At the flying speed of 70 to 75 km/h the scan spacing is approximately 300 mm apart, resulting in a point density of 10 points per m^2.

A video system is also used to provide a visual image of the scanned corridor. This system consists of a colour S-VHS video camera mounted to the laser, and another one placed in an oblique direction looking forward. The VHS/S-VHS video recorder records video images of the laser-scanned terrain using both the forward and downward looking cameras.

A Microsoft Windows post processing system called FLIP 7, installed on an Intel Pentium PC and specially developed for this purpose by John E. Chance & Associates, performs the first level "in the field" processing of the scanned (FLI-MAP) data. It also incorporates an appropriate interface for the video player. FLIP 7 plots the surveyed data points in plan, side, and longitudinal view and is capable of moving the forward and downward looking videos over the plotted section. Assets are located by drawing polylines or points on assets as seen in the plotted data. As assets are drawn on the data, each drawn point is given the longitude, latitude, and elevation of the nearest scanned or ground point. Each drawn object is identified by linking attributes describing the asset.

19.4 Integrating a Railway Asset Management System

As mentioned previously, a Railway AMS should include and combine all kinds of specialised monitoring, data collection, and decision support systems. This should be the case for track, but also for all other railway infrastructure elements like bridges, switches and crossings, overhead lines, level crossings, tunnels, culverts, etc. Some of these systems will be given special consideration later on in the text. AMS should also incorporate issues like environmental and hazard management and emergency response systems.

Once integrated, an AMS should serve the needs of all the parties which are in anyway connected to the railway system, such as the infrastructure owners, railway contracting or traffic operating companies, or any other. They all should make use of the AMS, extract the data needed for their everyday or long-term strategic purposes, and also feed the appropriate data back to the system.

Figure 19.11: GIS background layout of an AMS [62]

The final "look" of the system and some of its features could be similar to those presented in the Figure 19.11, Figure 19.12, and Figure 19.13. This last Figure presents its overall structure. The final "look" should allow for seamless integration between geographical mapping, database management, and multimedia technologies in order to efficiently manage data in today's railway environment. It should also involve such technologies as the Internet to provide worldwide access to all railway information, and enable centralised data management to be performed quickly and easily. It should handle issues like passing information back and forth between various users and their departments, updating data bases, and integrating digital information among the users.

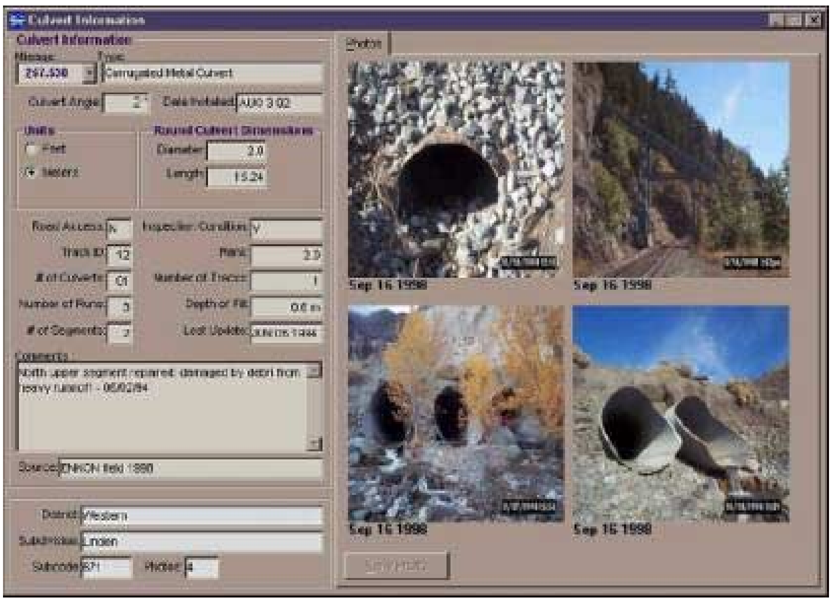


Figure 19.12: GIS background layout of an AMS (2) [62]

20 LIFE CYCLE COST ANALYSIS

20.1 Life Cycle Costing

In the 1990s the setting for infrastructure management changed for many railways, especially in Europe. EU directive 91/440 requires that a separate organisation has to provide the railway infrastructure in order to create profit-driven transport operators and transparent cost accounting of infrastructure maintenance and operations [94]. The railway restructuring leads to the introduction of user charging and performance regimes. The operators have to pay access charges for using the railway assets, while the infrastructure manager has to pay penalties in case of unplanned disruption. Decisions in design and maintenance have to be based on estimates of availability, reliability and maintenance costs in order to minimise the total (long-term) costs of ownership for the infrastructure owner.

In the Dutch railway sector three 'change programmes' are initiated since the mid 90s in order to deal with the changed management conditions:

1. *'Life cycle management'* (LCM) aims at the realisation of a systematic approach to underpin and optimize investments in new construction, maintenance and renewal. Costs of ownership, including penalties for track possessions, have to be analysed for a period of 50 years. Since last year the regional maintenance planning staff is obliged to identify the feasible investment and life-lengthening maintenance solutions and to quantify their assumptions on investment and maintenance costs using a special computer application [198].

2. *'Performance-based contracts'* are being introduced for the maintenance and incident management. Contractors with approved quality control systems can acquire this type of contract for periods of 5 years. Their efforts will increasingly be monitored based on agreed performance indicators [254].

3. *'Maintenance window scheduling'* is triggered by more stringent safety demands for maintenance works. Maintenance and renewals will be clustered in periodic maintenance windows (sometimes called slots): the Ministry of Transport will not allow maintenance during operations [110].

The necessity of an Asset Management System (AMS) as described in Chapter 19 for supporting the track maintenance seems to be obvious. For adequate planning insight in the relationships between transport volumes, infrastructure quality, maintenance efforts and availability and reliability *in the long term* is a prerequisite. A Life Cycle Costing approach is presented in this chapter that is able to help develop the AMS concept. Since the implementation of the AMS is in many railways only partly realised, the way to deal with lacking and unreliable data is covered as well in the examples being:

– Appraisal of track designs for the HSL South for an international consortium;

– Revision of track maintenance policy on the Dutch conventional network.

In this Section the general principles of Life Cycle Costing (LCC) are introduced. Section 20.2 contains an outline of a computer application used for life cycle cost analysis of railway track at TU Delft. Two studies are presented shortly in Section 20.3.

20.1.1 Life Cycle Costing principles

Since railway infrastructure, and especially the railway track, has a long life span and investments are very costly, decision makers have to consider the long-term cost impacts in the construction, maintenance and transportation processes. A preventive maintenance regime can for instance postpone renewals and reduce traffic disruptions.

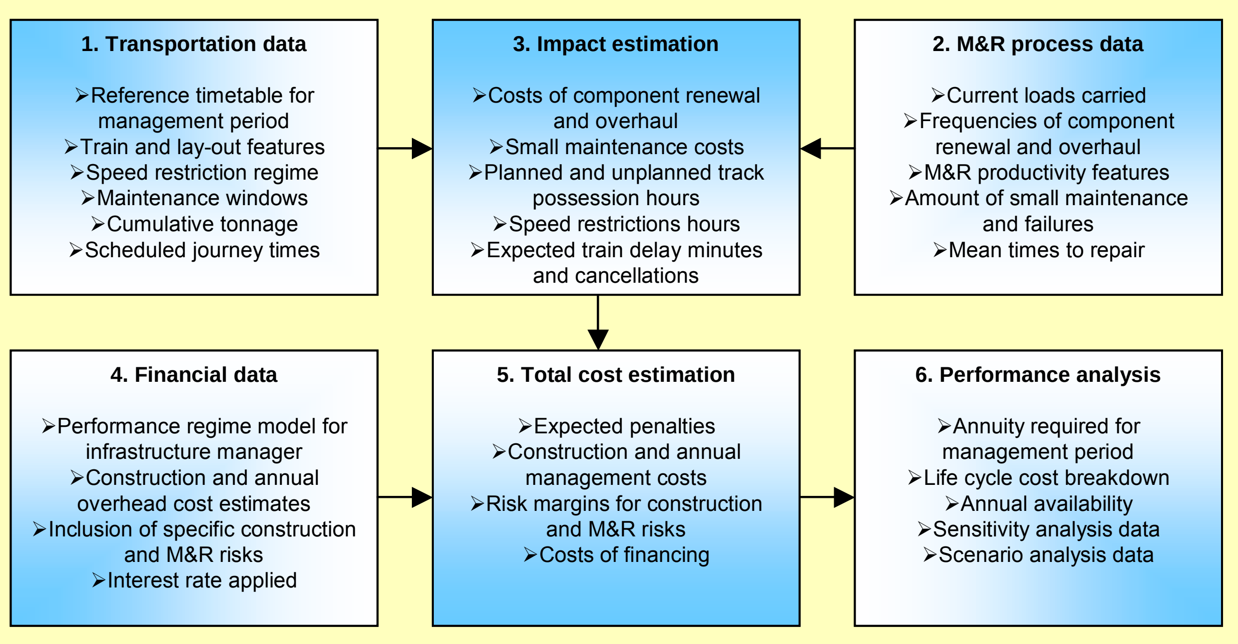


Figure 20.2: Life Cycle Cost DSS model-base

2. Maintenance and renewal analysis

A second starting point is the collection of key data on the maintenance and renewal processes for the track and switch components. First, data on the lifetime expectancy and overhaul and renewal thresholds is needed. Secondly, data on the overhaul and renewal methods is needed, such as the production speed in relation to the duration of a track possession (work efficiency, start-up and finishing time) and the costs per kilometre and per work shift. Besides, data on the maintenance and failure repair process is needed, such as the response and repair time and the annual small maintenance and inspection cost (per ton or per year - per km).
The information should be available in so-called 'Maintenance Concepts' which contain all the information related to the maintenance of a specified asset e.g. for 'a switch 1:9 UIC54 wooden sleepers, depreciation group UIC-3'. If these concepts are not available, a Failure Mode Effect Analysis (FMEA) should be organised. With the FMEA method the knowledge of design and maintenance experts is systematically used to identify risks and develop a maintenance plan [16]. In the DSS a number of specific risks can be selected for innovative track structures, such as the chance on cracking of the concrete supporting bed or early deterioration of elastic materials in case of slab tracks.

3. Impact estimation

By combining the M&R and timetable data the cost impacts during the maintenance management period can be forecasted. First, the volume of renewals and major overhaul, such as tamping and grinding, is scheduled. A number of years for completion of the activity can be included, which depends on the available work capacity and maintenance windows. Secondly, the number of work shifts needed in the specific years is estimated using the data on productivity rates and the duration of maintenance windows (see Figure 20.3). Thirdly, the costs and speed restriction hours due to renewal and overhaul in the specific years is set using the cost rates and speed restriction regime i.e. the number of days with a specified speed limit.

More or less the same calculation takes place for the small maintenance and failure data, except that the estimates are extracted from the FMEA or Maintenance Concepts. The maintenance costs and unplanned track possession time is simply related to the cumulative tonnage or service years of the asset (see Figure 20.4).

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