Specification based non-empirical ballastless track development

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Abstract
For the development of ballastless track for the Dutch high-speed line a non-empirical design method based on pre-defined specifications is made in accordance to European specifications on railway RAMS. The various phases of the design method, which are related to the lifecycle of a system, are described. The design of direct fastening track is used to illustrate the design method. The non-empirical design method has proven to be useful for ballastless track development and gives full understanding in the track behaviour.

1 Introduction
Track developments have always been done on the basis of empirical design methods. New track designs had to be tested under normal trainloads for a few years before approval for application could be granted. The development of ballastless track for the first Dutch high-speed line, HSL-Zuid, started no different. Due to the fact that it proved impossible to build a test track for testing with high-speed in time, a different design method was opted for. This design method is based on EN50126 “Railway applications – The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS)”.

This paper describes the translation of the electrotechnical standard to a design method for ballastless track. The design method will be illustrated by the development of the reference ballastless track design for HSL-Zuid.

2 European standard EN50126
The European standard EN50126 defines a process, based on the system lifecycle, for managing reliability, availability, maintainability and safety (RAMS) for railway applications. Managing RAMS ensures that a railway system can achieve a defined level of traffic in a given time and safely. RAMS of railway applications have a clear influence on the quality of service that is delivered to the train passenger. Although EN50126 is an electrotechnical standard, it can be applied for all railway applications.

RAMS according to EN50126 is:

“...a characteristic of a system’s long term operation and is achieved by application of established engineering concepts, methods, tools and techniques throughout the lifecycle of the system. The RAMS of a system can be characterised as a qualitative and quantitative indicator of the degree that the system, or the sub-systems and components comprising that system, can be relied upon to function as specified and to be both available and safe.”

The philosophy of managing RAMS is based on consideration of the complete lifecycle. As this paper describes the design phase of the track system, the focus will be on the first six phases of the lifecycle of a system.

The first six phases in the lifecycle of a system as described in EN50126 are depicted in figure 1. The phase related tasks, with respect to RAMS, have been adjusted for the specific design of track structures. These are, apart from organisational aspects, enumerated in table 1.
System acceptance method

The phase related tasks for the design of track structures as shown in table 1 are translated into a system acceptance method that is used to develop the ballastless track for HSL-Zuid. The system acceptance method is shown in figure 2. The rimmed boxes with numbers refer to the various lifecycle phases as shown in figure 1. The input for the system acceptance method is formed by the top-level specifications. On the basis of these specifications, a track concept is selected. In lifecycle phase two, the track concept is worked out in more detail and interfaces with other systems than the track itself are identified. In phase three, a failure mode analysis is conducted of the track structure, in which all possible failures are identified. This results in the identification of researches to be done. The top-level requirements and the identified researches are fed into the verification matrix, forming phase four of the systems lifecycle. Specific research will solve any outstanding questions in the verification matrix as part of phase six. The design process results in the final track design and various specifications.

3 System acceptance method

The phase related tasks for the design of track structures as shown in table 1 are translated into a system acceptance method that is used to develop the ballastless track for HSL-Zuid. The system acceptance method is shown in figure 2. The rimmed boxes with numbers refer to the various lifecycle phases as shown in figure 1. The input for the system acceptance method is formed by the top-level specifications. On the basis of these specifications, a track concept is selected. In lifecycle phase two, the track concept is worked out in more detail and interfaces with other systems than the track itself are identified. In phase three, a failure mode analysis is conducted of the track structure, in which all possible failures are identified. This results in the identification of researches to be done. The top-level requirements and the identified researches are fed into the verification matrix, forming phase four of the systems lifecycle. Specific research will solve any outstanding questions in the verification matrix as part of phase six. The design process results in the final track design and various specifications.
In the following, the steps undertaken in each phase 1–4 and 6 of the system lifecycle will be addressed on the basis of the development of ballastless track for the Dutch high-speed line HSL-Zuid.

4 Lifecycle phase 1: concept

4.1 Introduction
In the first phase of the system lifecycle three actions are undertaken:
- determination of top-level specifications
- selection of type of track structure
- consideration of RAMS implications

These actions will be discussed in the following.

4.2 Top level specifications
The project starts with the determination of the top-level specifications. On the one hand these are formed by RAMS specifications and on the other hand by technical top-level specifications. The latter are based on the “Technical Specifications for Interoperability (TSI)” and on national specifications, adapted to high-speed lines.

4.3 Track type selection
The type of ballastless track to be developed was chosen based on a worldwide survey of ballastless track. Track specialists and sites were visited in Italy, Japan, Germany, France, Swiss and the Netherlands.
Ballastless track structures were split into four groups:
1. prefab slab track, see figure 3
2. sleeper systems, see figure 4
3. individual supports, see figure 5
4. embedded rail construction, see figure 6
Fig. 3: example of prefab slab track

Fig. 4: example of sleeper system
For the specific situation at HSL-Zuid, with 75% of the track built on viaducts, bridges and in tunnels and an allowable track construction depth of 360 mm, ballastless track structures from the groups “individual supports” and “embedded rail construction” were found suited. Direct fastening track, as part of the group “individual supports”, and embedded rail construction were developed for application on HSL-Zuid. In this paper, the development of direct fastening track, see figure 5 and 7 is used to illustrate the non-empirical design method.
4.4 Consideration of RAMS implications

Direct fastening track has been used at the Netherlands Railways on bridges, viaducts and in tunnels since 1965. In order to obtain RAMS data of the track structure as well as to estimate the proper lifecycle costs, a track quality assessment of 15 objects was carried out.

For this purpose an assessment method was set up. The assessment method is based on assessing each individual fastening. For every fastening the present defects are identified, split up for each individual component or combination of components. The identified (combination of) defects are expressed as a percentage of the total amount of fastenings. Furthermore, for components of the baseplate fastening, the location of the defect, i.e. inside or outside the track, is determined as to identify a possible relationship between the type of defect and the place of occurrence. Besides the described defects, the curve radius, cant, speed and tonnage are determined.

The assessment clearly proved the relationship between construction and longevity. In this respect, the construction tolerances of the concrete plinth are of great importance, as is the accuracy of the drilling of the holes for the anchors. The effect of application of different types of track components on the longevity is determined.

The output of the assessment showed that the lifecycle cost of direct fastening track on concrete structures amounts to 54% of the cost for ballasted track on concrete structures, considering a lifecycle of 90 years.

The results are also used in object specifications, the specifications for the various track components, as well as construction and maintenance specifications.

4.5 Output of phase 1

The output of phase 1 is:
- a complete set of specifications on top-level regarding RAMS as well as technical aspects
- direct fastening track as track concept
- insight in RAMS implications of direct fastening track
- lifecycle cost information
- first information for object, construction and maintenance specifications

5 Lifecycle phase 2: system definition and application conditions

5.1 Introduction

With the results of the first phase, the system itself as well as its boundaries and application conditions have to be determined.

As part of the system definition, the configuration of the chosen type of track structure has to be determined, i.e. the type of rail and the support distance. Regarding the application conditions, the different substructures on which the track has to be applied has to be investigated.

These two items will be discussed in the following.
5.2 Optimisation of track components

Standard direct fastening track at the Netherlands Railways consists of UIC54 rails and a distance between adjacent supports of 0.60 meters. In order to optimise the rail profile and the support distance a 2D-computer model was made that also incorporates the stiffness and damping properties of the support to assess the dynamic behaviour of various combinations of track parameters. The considered variations of the track parameters are depicted in table 2.

<table>
<thead>
<tr>
<th>Rail profile</th>
<th>Distance between supports [m]</th>
<th>Dynamic stiffness [kN/m]</th>
<th>Damping [kNs/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>UIC54</td>
<td>0.60</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>UIC60</td>
<td>0.65</td>
<td>30</td>
<td>6</td>
</tr>
<tr>
<td>AREA136</td>
<td>0.70</td>
<td>40</td>
<td>10</td>
</tr>
</tbody>
</table>

*Table 2: Considered track parameters*

The dynamic behaviour of the various combinations of track parameters were assessed to their wear and noise emission properties. Figure 8 shows typical results of wear calculations as figure 9 shows typical results of noise calculations.

*Fig 8: Frequency response functions*  
*Fig 9: Distance damping*

The optimal combination of rail profile and distance between supports was found to be UIC60 and 0.65 m. Stiffness and damping characteristics were found to be depending on the type of substructure.
5.3 Types of substructure
The HSL-Zuid is characterised by different substructure categories with different settlement behaviour as explained in table 3.

<table>
<thead>
<tr>
<th>Substructure</th>
<th>Description</th>
<th>Max. required vertical adjustability track</th>
<th>Percentage of the line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category I</td>
<td>settlement free</td>
<td>0 mm</td>
<td>67%</td>
</tr>
<tr>
<td>Category II</td>
<td>limited settlement</td>
<td>30 mm</td>
<td>25%</td>
</tr>
<tr>
<td>Category III</td>
<td>sensible to settlements</td>
<td>50 mm</td>
<td>8%</td>
</tr>
</tbody>
</table>

Table 3: various substructure categories

Height adjustments up to 30 mm can be realised by applying shims between the baseplate and the baseplate pad, as shown in figure 10. This requires the anchors to have sufficient length at the topside. It was decided to apply the same anchors for both substructure categories I and II so that 92% of the line would be covered by standard track components. This does also allow for compensating unexpected settlements of category I substructure.

Fig. 10: realisation of adjustability for substructure categories I and II

The needed height adjustability of 50 mm for substructure category III can be realised in three steps, as shown in figure 11. The first step up to 20 – 30 mm is equal to category I and II. In the second step the 20 – 30 mm thick shims are replaced by a non-shrinking epoxy grout. In the third step the final adjustments up to 50 mm are realised equal to step one. This method requires extra long anchors and springs with a different length for step one and three.

Fig. 11: realisation of adjustability in three steps for substructure category III
5.4 Output of phase 2
The output of phase 2 is:
- well defined track structure with UIC60 rail and support distance of 0.65 meters
- one standard track and one special track for various substructures

6 Lifecycle phase 3: risk analysis

6.1 Introduction
A risk analysis is made from every track variant in order to identify possible weaknesses of the track structure. On the basis of these weaknesses, specific researches will be identified.

6.2 Failure mode analysis
Risk analysis is performed with the help of a failure mode analysis. For the purpose of the failure mode analysis the track structure is divided into four main elements:
- rail
- rail fastening
- foundation
- interface with substructure

The main elements are split up in all existing track components. For every track component all possible failures are described as well as the cause, effect and top-level effect. The risk level is determined as a combination of the top-level effect and the likelihood of occurrence. Possible actions are dedicated researches with either computer models, laboratory test or literature studies. For every research the loads that are to be taken into considerations are specified. A summarised example of the failure mode analysis is shown in table 4.

<table>
<thead>
<tr>
<th>Main element</th>
<th>Component</th>
<th>Possible failure</th>
<th>Cause</th>
<th>Effect</th>
<th>Top level effect</th>
<th>Risk level</th>
<th>Type of research</th>
<th>Loading spec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>rail</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rail fastening</td>
<td>railclip</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>foundation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>substructure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>interface</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Table 4: Failure mode analysis including example (summarised)

6.3 Output of phase 3
The completed failure mode analyses give full insight in all possible failures of the track structure. The researches that are identified in the failure mode analysis are grouped if possible. The resulting researches that have to be carried out are listed below, grouped by type of research:

- computer modelling
  - assessment of track component strength
  - consideration of failure cases

- laboratory test
  - properties of elastic materials
  - properties of adhesive and anchoring force
behaviour of complete track structure

literature / site survey
- rail properties
- railclip properties
- experience with reference track structure

design calculations
- rail fastening strength
- baseplate fastening strength

A number of these researches will be discussed in lifecycle phase six.

7 Lifecycle phase 4: system requirements
A verification matrix controls the system requirements. The top-level specifications as determined in the concept phase are translated into system requirements and form together with the identified researches from the failure mode analysis the basis of the verification matrix. This verification matrix must ensure that all requirements are met and therefore forms a loop with the design phase. Once the design of phase six satisfies all requirements as listed in the verification matrix, the final track design is completed and object, construction and maintenance specifications can be finalised.

8 Lifecycle phase 6: design
8.1 Introduction
In phase six of the system lifecycle, the actual design is made. In addition, in this phase all actions that are identified in the verification matrix have to be completed. In the following one design item and five researches done in laboratory and with computer models will be discussed.

8.2 Design of baseplate
On of the components that were designed is the baseplate. The design of the baseplate for UIC60 rail and rail seat inclination 1:20 is based on the existing baseplate for UIC54 rail and rail seat inclination 1:40.
The location of the holes for the anchors is chosen in such a way that that existing UIC54 1:40 track could be exchanged with UIC60 1:20 track using the same anchors.
Two alternative manufacturing techniques were tried: casting and forging. It was found that the casted baseplates had smaller tolerances that the forged baseplates, which exceeded the allowed tolerances.
Furthermore, the effect of anti-corrosion treatment was investigated. It was found that that the flatness of the bottom of the baseplate was higher without treatment but that with treatment the flatness was still within the tolerances.
The results of the test with various manufacturing techniques were translated into object specifications.

8.3 Laboratory test of elastic materials
The baseplate pad and railpad provide the elasticity of the track structure. The characteristics of these materials were tested to their tensile and compressive strength, stress-strain relationship, temperature stability and ageing. Various materials from various suppliers were tested. The main findings of the test were:
- Characteristics from elastic materials change with lower temperatures so that they become significantly stiffer. It was found that this changing point for many materials was within the specified temperature range.
- Characteristics from elastic materials change with high strains so that they become significantly stiffer. It was found that some materials stiffened significantly within the under normal conditions occurring strains.

As a result, object specifications were completed with requirements for temperature stability and stress-strain relationships.

8.4 Laboratory test of the fastening of the anchor
Laboratory test were conducted on a great number of test specimens to establish the anchoring force of the rail anchor in the concrete. In these test the influence of incorrect construction was taken into account.
The following construction cases were considered:
- normal (optimal) construction
- leaning anchor
- wet bore hole (soaked)
incomplete filled holes

Three types of test were conducted:
- determination of vertical pull out force
- fatigue test with four million horizontal load cycle
- determination of vertical pull out force after fatigue test

![Fig. 12: example of test result](image)

It was found that the vertical pull out force in all cases was over five times the required value. The elastic and permanent deformations during the fatigue test were found to be small, except for the cases ‘wet borehole’ and ‘incomplete filled holes’.

It was concluded that the vertical pull out force meets the requirements and is not influenced by incorrect construction. The horizontal stability however requires complete filled holes and relatively dry conditions. These findings were incorporated in the construction specifications.

8.5 Laboratory test of the complete track
In order to test the behaviour of all track components together and to validate the 3-D computer model, laboratory tests on complete supports were conducted, see figure 13.

![Fig. 13: laboratory tests on complete supports](image)
The rail is subjected to a combined horizontal and vertical force that is representative for the maximum load that can be exerted to the rail according to the top-level requirements. The displacements of the support are measured at 12 points as shown in figure 14. The tests confirmed the expected behaviour of the support and provided the needed results for validation of the 3D-computer models.

8.6 Assessment of track components strength

Vertical trainloads are directly transferred from the rail through the baseplate to the concrete substructure. Horizontal loads, however, have a larger impact on the fastening and therefore the strength of the various track components need to be verified. For this purpose, a 3D-computer model of the direct fastening track is made that consists of seven supports as shown in figure 15. The middle support of which a detail is shown in figure 16 is loaded with a representative trainload and the stresses and strains in all track components are determined.
Fig. 15: overview of middle five supports

Fig. 16: detail of middle fastening
The computer model is extensively validated on three levels:

- level 1: validation of the model itself
- level 2: validation of the input parameters
- level 3: validation of the results

In level 1, the number and type of elements of which the model is composed are determined. For level 2 validation the laboratory tests on elastic components and anchors are used. For level 3 validation the laboratory tests on complete supports are used.

The model produces complete insight in the stress and strain distribution in all components. An example of the stress distribution in the baseplate is shown in figure 17.

The model is also used to determine the optimal combination of elasticity of the collar bush and the baseplate pad. It was found that the stiffness combination of both components determines the stress distribution in all track components as well as the horizontal and vertical rail displacements. With regard to the specifications the allowable stiffness area was determined, the area in which all requirements are satisfied. The percentages on the axis of this area as shown in figure 18 refer to the stiffness of the track concept as in use at the Netherlands Railways. The optimal stiffness combination was found to be 100% for the baseplate pad and 10% for the collar bush.
The calculation results give full insight in the stress and strain distribution of the fastening and allowed for optimisation on the level of individual track components. The results were also used in the object specifications.

8.7 Failure case behaviour
Incorporating failure cases in the design must ensure the safety of the design. One of the incorporated failure cases was the failure of an anchor. Due to construction faults or unforeseen circumstances, failure of an anchor is possible. Failure of one anchor may not cause other anchors to fail. The 3D-computer model as described in the former chapter calculates the maximum stress and strain levels in case of 1, 3 or 9 supports are affected in order to check occurrence of a domino effect. In every case the broken anchor is assumed to be on the outside of the track, as this will have the greatest impact on the stress and strain levels. In figure 19 the computer model for this failure case is shown.
In case of a normal support, both anchors transfer the horizontal load. In the three failure cases the horizontal load at the affected supports is distributed by only one anchor. As a result the stresses in almost all components increase and the horizontal rail displacement increases as well. Because the horizontal stiffness of one support is decreased, the horizontal load will be distributed over more supports. So in spite of all load being concentrated at the middle support at one anchor, the load will be spread over the adjacent support and the stress in the component will subsequently not be twice as large.

In figure 20 the stress increase in the various track components is shown.

![Graph showing relative stress increase in various track components](image)

*Fig 20: relative stress increase in various track components*

From these calculations it is concluded that a domino effect will not occur in the event of a broken anchor.

### 8.8 Output of phase 6

Phase six has resulted in the final track design with optimised track components that are tested to their behaviour in laboratory. The effect of failure cases is determined to ensure safety. The design is reviewed to the system requirements as listed in the verification matrix.

Object specifications for all track components are made as well as construction and maintenance specifications.

### 9 Conclusions

The non-empirical design method based on pre-defined specifications has proven to be very useful for ballastless track development. This design method gives more understanding of track behaviour than the empirical methods do. Where an empirical method only gives information whether the tested track does or does not fail at the specific location under the specific train loading provides the non-empirical design method full insight in the track behaviour as well as stress distribution through all track components and their reserves to the stress limit. Consequently, the non-empirical design method gives more possibilities for optimisation of the overall design and of components.

The failure mode analysis is a powerful tool to understand all failure mechanisms as weaknesses are identified and worked out in detail.

The described design method is in accordance to European specifications on railway RAMS and is therefore suited to be used in design & construct contracts where RAMS has to be proven in safety cases.