Recording, Estimating and Managing the Dynamic Behaviour of Railway Structures

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Abstract
This paper presents the development of a recording and analysing method for the structural condition of railway tracks, called Dynatrack. The demands on railway track structures are increasing year by year due to more frequent and heavier transport of passengers and goods at higher speeds through more densely populated areas. In this context, there is a need for a clear description of track dynamics, as this is the key issue with respect to environment (noise and vibration) as well as to track degradation. A prominent role for assessing the railway track dynamics is reserved for the frequency response function, which is recorded via modal analysis and simulated via finite element software. In this paper attention is paid to these two for the assessment of track dynamic behaviour with examples of a proven and still promising track fastening system.

1. Introduction

Nowadays many different railway track structures are applied all over the world. Railway track structures differ because of a wide variety in requirements. Dependent on the location where they are applied, vibration transmission or noise radiation should be prevented. Sometimes operational conditions (e.g. high speeds) impose special requirements to stability of tracks, maintenance, to positioning accuracy, availability, etc. The dynamic behaviour of railway track structures is directly related to most of these items. The goal of the research project Dynatrack is the development of methods for the evaluation of dynamic properties of several types of track for specific applications. This involves both a decision support system for track management as well as a recording system in order to check the specific track properties at any time and at any place.

2. Methods

2.1 Recording methods

To record dynamic behaviour of railway track structures, two closely related methods have been developed. The first method concentrates on the determination of *component* properties *in laboratory* test set-ups or small sized assembled track specimen, under specific loading and climatological conditions. The second method is to be applied *in the field on existing tracks.* Both methods feature a hammer excitation test with an instrumented impact hammer and several accelerometers recording component vibration behaviour at well-specified points. In principle the method allows recording of vibrations in a range between 30 Hz and 3 kHz. More details on this method are given in [1]. The so-achieved data are best presented in frequency response functions (FRF), clearly showing resonant frequencies, which contain information of dynamic and geometrical properties of the components in the structure. In this paper only the amplitude and no phase data of the FRFs are displayed. The response functions are in receptance format, relating force input and displacement output according to:

$$H_{xF}(f) = \frac{S_{xF}(f)}{S_{FF}(f)} = \frac{1}{(2\pi f)^2} \cdot \frac{S_{aF}(f)}{S_{FF}(f)} \qquad (1)$$

herein:

H_{xF}: complex receptance function (FRF), containing amplitude [m/N] and phase data [-]
S_{xF}: complex cross-spectrum of displacement (output) [mN/s]
S_{aF}: complex cross-spectrum of acceleration (output) [mN/s^3]
S_{FF}: power spectrum of force (input) [N^2/s]
f: frequency [Hz]

2.1.1 Testing track components

In Fig. 1, a typical rail fastening system for ballastless railway track structures is displayed. It has been installed since the late 1950s on several concrete and steel bridges and in tunnels in the Netherlands, both for mainlines and metro lines. This system is now also considered for high speed application [2].

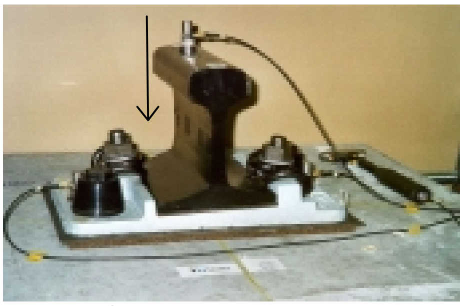

Fig. 1: Single rail fastening assembly HSL tested in laboratory

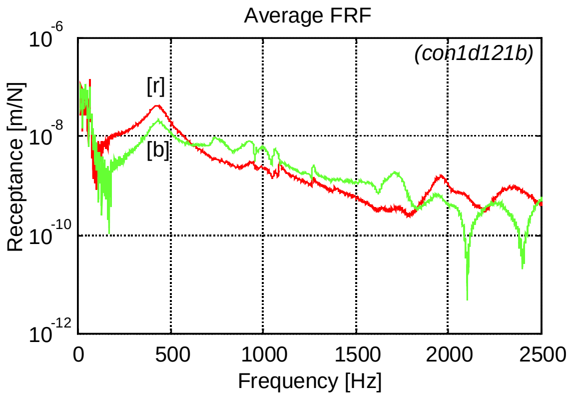

Fig. 2: FRF of vertical behaviour of single rail fastening assembly: [r] recorded at railhead, [b] at baseplate

Fig. 2 shows the FRFs in vertical direction of a single rail fastening assembly for HSL, which was tested in the laboratory. Modal testing enables to collect output at different positions of the fastening system, such as railhead [r] and baseplate [b]. This facilitates distinguishing different vibration modes. While concentrating on vertical dynamic behaviour of the system, the principal mode is observed at 420 Hz, where rail and baseplate are jointly vibrating on the elastic baseplate pad.

In Fig. 3 the FRFs of a comparable rail fastening system is shown for light-rail application by RET. At 290 Hz, rail and baseplate are jointly vibrating on the baseplate pad. In order to reduce energy transmission, an additional elastic layer is applied underneath a concrete block, on which the fastening system is mounted. The resonant frequency of the joint vibration of rail, baseplate and concrete block is 100 Hz. The elastic layer underneath the block is a cast-in-place self-hardening compound (encasing).

Apart from vertical vibration modes, modes in other directions can be exited and recorded as well. This depends on recording positions, input direction, geometrical imperfections and other restrictions. It is verified that vertical modes are dominating all the (presented) results of these tests.

Fig. 3: Single rail fastening assembly RET on a block

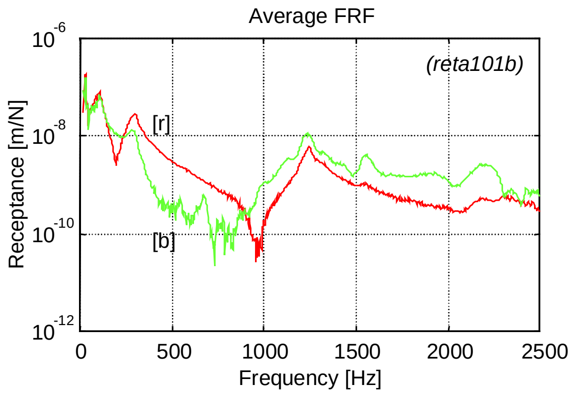

Fig. 4: FRF of vertical behaviour of single rail fastening assembly on a block: [r] recorded at railhead, [b] at baseplate

In section 2.2, a system identification method will be applied to extract dynamic properties of both baseplate pads and block encasing, fulfilling the recorded behaviour.

2.1.2 Testing track structures

Compared to component testing in the laboratory, testing railway track structures in the field is much more complicated. It is however considered important for quality assessment of new tracks or track in operation. A set of recording positions is selected in the direct neighbourhood of the excitation position. Fig. 5 shows a typical set-up, installed on a track fastening system at Rotterdam Metro.

Fig. 5: Railway track structure at RET tested in the field

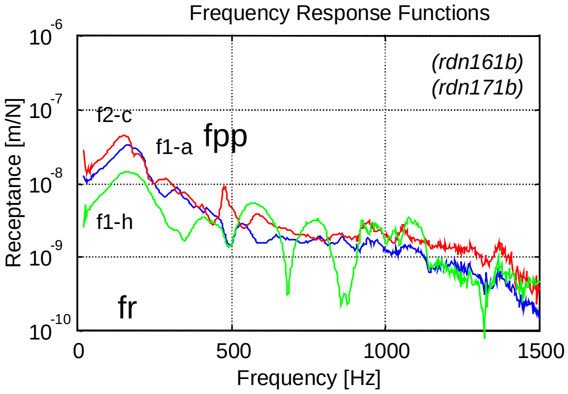

Fig. 6: Recorded FRF of a railway track tested in the field

In Fig. 6 the FRFs at three different positions (a, c and h in Fig. 5) are displayed by exciting the rail above a support (f1), and by exciting mid-span (f2 in Fig. 5). The differences between the FRFs at different positions are apparent and contribute in assigning the several vertical vibration modes of the structure, which are 160 Hz (f_r) for rail plus baseplate and 480 Hz (f_{pp}) for bending of rail between supports. The latter vertical vibration mode is called pin-pin mode, referring to the shape of the vibration. In this mode, the rail is vibrating like standing waves in a rope with steady nodes at the supports.

Vertical modes are expected to dominate in these tests, but especially field tests will show much more modes than only vertical. A keen interpretation of the results is thus necessary.

2.2 Simple system identification methods

Parts of FRFs, in particular the resonant frequencies, supply detailed information on component properties. The extraction of these component properties is possible thanks to curve-fit routines. For testing the component properties of a single track fastening system in the laboratory, one or two DOF mass-spring systems with dampers may be sufficient in describing the vibration behaviour. In principle, only stiffness and damping parameter values of the assembled system are unknown. Via least square optimisation, the FRF of the model is tuned to cover the recorded FRF in a frequency band around the resonant frequency related to the particular vibration mode(s). This procedure is called curve-fitting.

Fig. 7a shows an example of one DOF mass-spring curve-fit on the HSL rail fastening assembly in the laboratory, while Fig. 7b shows a comparable example of a two DOF mass-spring curve-fit on the RET rail fastening assembly. The curve-fits are shown as dotted lines.

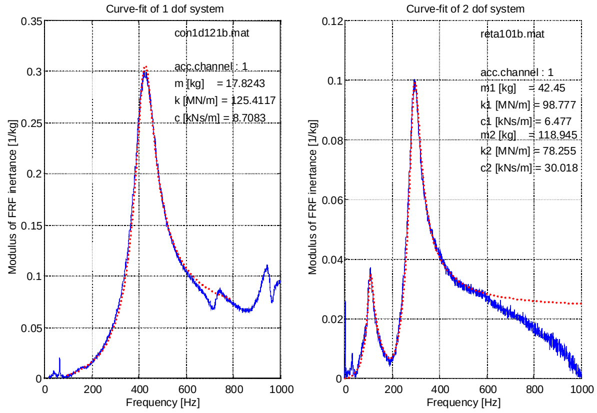

Fig. 7a,b: FRFs of curve-fits (dotted lines) and recordings (continuous lines) of HSL and RET single rail fastening assemblies

	HSL	RET
mass rail section [kg]	12	36.7
mass baseplate [kg]	5.8	5.8
stiffness baseplate pad [MN/m]	125	98.8
damping baseplate pad [kNs/m]	8.7	6.5
mass block [kg]	-	119
stiffness encasing [MN/m]	-	78.3
damping encasing [kNs/m]	-	30.0

Table 1: Results of curve-fitting

The parameter values in Table 1 are the final values of the one and two DOF curve-fits with minimisation of error for the recorded FRFs at railhead level. Linear behaviour is assumed which is a consequence of applying FFT on time-domain recordings. Further stiffness and damping values are representing impact loading situation, which differs considerably from low-frequent (1-30 Hz) or static loading. The final curve-fit values are according to models, which are comparable to the single fastening assemblies tested in the laboratory. But the models are however far from comparable to the track structure tested in the field. How there is dealt with these recordings in the field is explained in section 3.3.

2.3 Other identification results

Many fastening systems have been tested in the laboratory in order to determine impact stiffness and damping. Rail pads are an essential part in fastening systems as they avoid transmission of high frequent dynamic vibrations. They protect e.g. concrete components for cracking. In Fig. 8 the impact stiffness and damping of several rail pads are collected, with additional data from [3]. The values are determined via 1 DOF mass-spring curve-fits on recorded FRFs. All recordings took place at 20 kN static pre-load, while in practice, the pre-load on rail pads (supplied by the clips at both sides of the rails) varies between 10 and 20 kN.

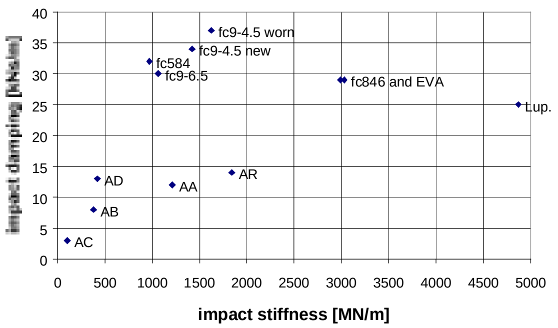

Fig. 8: Rail pad impact properties at 20 kN pre-load

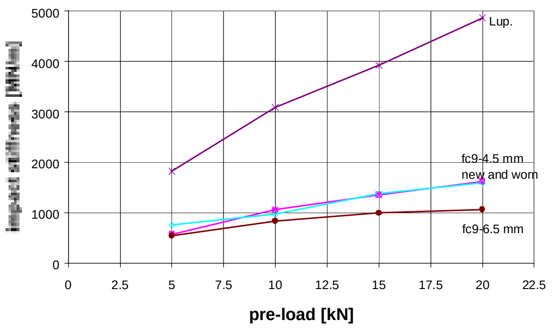

Fig. 9: Rail pad impact stiffness versus pre-load

Variation in static pre-load on the rail pads shows considerable differences in impact stiffness, which is shown in Fig. 9, and consequently in rail pad damping (not shown here). This is important to know, as during the in-service time of fastenings, the pre-load on rail pad tends to decrease.

Passing vehicles will increase the maximum total load on a single rail pad to roughly speaking half the load of a single wheel. Wheelloads are varying between 30 kN for trams without passengers to over 150 kN for some freight lines. Depending on the vehicle's speed, the loading is to be considered somewhere between static and dynamic. The impact stiffness of rail pads while loaded by a wheel will run at least to higher values than depicted in above graphs.

Fastening system should be designed, installed and maintained so that passing vehicles will not cause any damage. Examples of damage observed in the field, range from loose or broken clips, by consequence lost or even burnt rail pads and serious cracks in concrete blocks or sleepers.

3. Simulation methods

3.1 Finite element software

Frequency response functions of railway track structures can be calculated via analytical and numerical algorithms. The railway track simulation software RAIL is a numerical 2D finite element program, which can evaluate vibration behaviour of track structures due to impact loading. Besides this, RAIL also features track-vehicle interaction and other static and dynamic types of loading. The structural properties for the vehicle are extensive (multibody, interconnected) as well as for the track (contact elements, multilayer, shear and bending contributions). Moreover the model allows disturbances or imperfections in vehicle and track, e.g. loose fasteners, floating sleepers, transitions in supporting stiffness, rail surface irregularities, etc.. In RAIL the relation between stress and strain is assumed linear, which implies that parameter values for input should be chosen so that they comply with the considered situation. In Table 2 the input data for impact loading simulations, comparable to field measurements, is listed.

	HSL	RET
rail type (code)	UIC60	S49
total track length [m]	33.15	72.0
support spacing [m]	0.65	0.90
mass baseplate [kg]	5.8	5.8
stiffness baseplate pad [MN/m]	125	98.8
damping baseplate pad [kNs/m]	8.7	6.5
mass block [kg]	-	119
stiffness compound [MN/m]	-	78.3
damping compound [kNs/m]	-	30.0

Table 2: Simulation parameter values

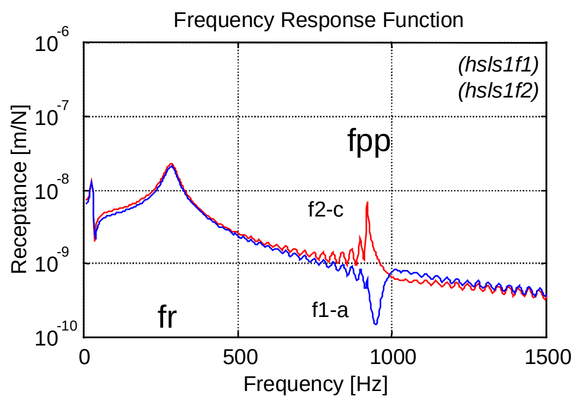

Fig. 10: Simulated FRF of HSL fastening system

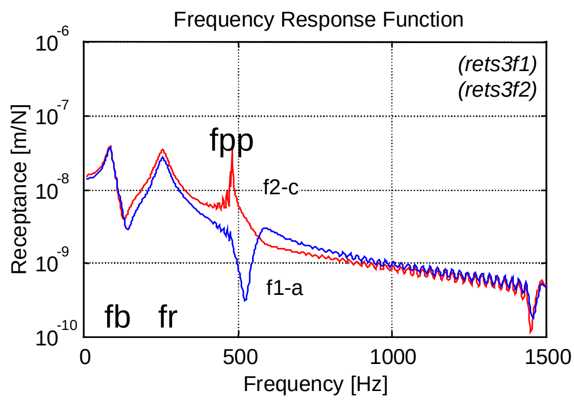

Fig. 11: Simulated FRF of RET fastening system on a block

In Fig. 10 and Fig. 11 FRFs of both track structures are shown which are based on the results of the tests of the fastening systems in the laboratory. The FRFs describe excitation above a support and mid-span.

3.2 Comparison with measured FRF

The RET track structure which is measured in the field is now compared with the simulated structure. In Fig. 12 the differences between the FRFs are from time to time considerable, in particular at the resonant frequencies f_r and f_{pp}.

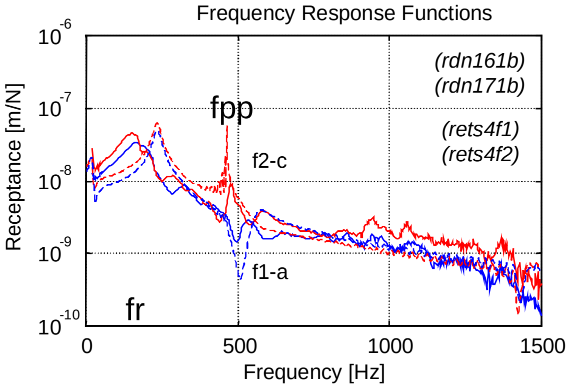

Fig. 12: Simulated (continuous lines) and recorded (dashed lines) FRFs of RET fastening system without a block

Most of the differences can be explained from two major effects:

1. Regarding the first vertical resonant frequency f_r a shift in frequency and amplitude is observed. This implies different field and simulation values for impact stiffness and damping of the baseplate pad. In particular lower stiffness is recorded than simulated. It is very plausible as the field conditions featured higher temperatures and presumably lower pre-loads than the laboratory testing conditions.
2. Regarding the differences around the pin-pin resonant frequency f_{pp}, the accuracy of the recording positions is significant. For both field recorded FRFs, the positions are at least 10 cm from the positions that have been simulated. This difference causes less apparent peaks and valleys at resonance and anti-resonance frequencies.

3.3 Simulation models for advanced system identification methods

Simple identification methods are perfectly able to find just a few parameter values via curve-fitting with a simple model. When recordings are made on complicated track structures, more advanced models are necessary to describe vibration behaviour, such as illustrated above. Advanced curve-fit routines make use of these models with parameters for several components, structural geometry and the inertia. The final curve-fit results and the total calculation time depend on the number of parameters and the maximum allowable error in the fit. Models in RAIL are likely to be implemented soon in such an advanced system identification method.

3.4 Extension of the reference design

In all forgoing simulations, the earlier discussed rail pad was left out. The introduction of this elastic layer between rail and baseplate has serious influence on the FRF of track systems. In Table 3, the additional impact properties of a rail pad are listed.

	HSL
support length [m]	0.12
stiffness rail pad [MN/m]	1400
damping rail pad [kNs/m]	32

Table 3: Additional simulation parameter values

In Fig. 10 on previous page, f_r clearly indicates the first principal vertical track resonance. For this vibration mode, only vertical stiffness of the support is activated. The major consequences of additionally modelling the rail pad have been made visible in Fig. 13. The numbers refer to the following list.

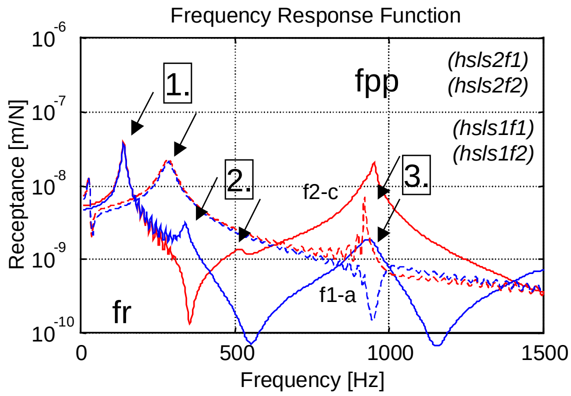

Fig. 13: Simulated FRF of HSL fastening system comprising rail pad and baseplate pad (continuous lines) and baseplate pad only (dashed lines)

1. f_r appears at a lower value, though the total vertical stiffness of the track is hardly lowered: rail pads are more than 10 times stiffer than baseplate pads;
2. several vertical resonant and anti-resonant frequencies occur either at position c or at a;
3. the vertical resonant frequency where the rail vibrates out-of phase with the baseplate interferes with f_{pp}.

By analysing vibration modes in detail, it turned out that rotational stiffness and damping of the supports in particular initiated the new vibration behaviour.

3.5 Variations to the reference design

Some variations in structural behaviour have been introduced in the extended reference design of the HSL fastening system, mentioned in previous section. A brief overview of three variations is interesting because it can assist in warning for unexpected behaviour.

1. Increasing support distance from 0.65 to 0.75m;
2. Introducing softer baseplate pads (impact stiffness minus 50%, damping unchanged);
3. Introducing softer railpads (impact stiffness minus 50%, damping unchanged).

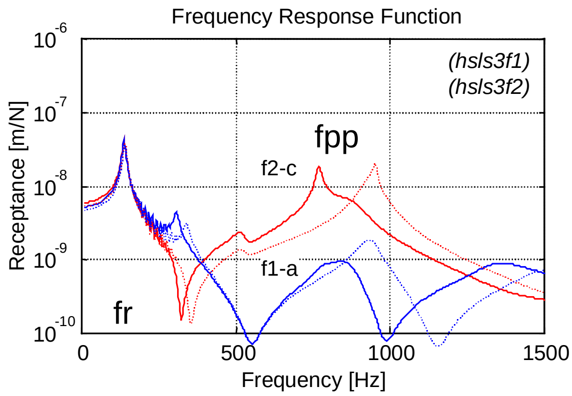

Fig. 14: Simulated FRF with increased support distance (continuous lines) and reference (dotted lines)

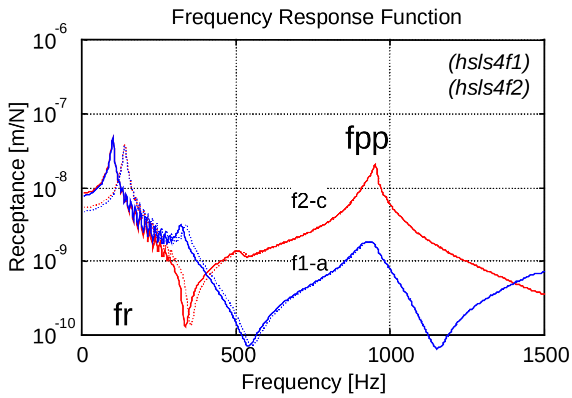

Fig. 15: Simulated FRF with decreased baseplate pad stiffness (continuous lines) and reference (dotted lines)

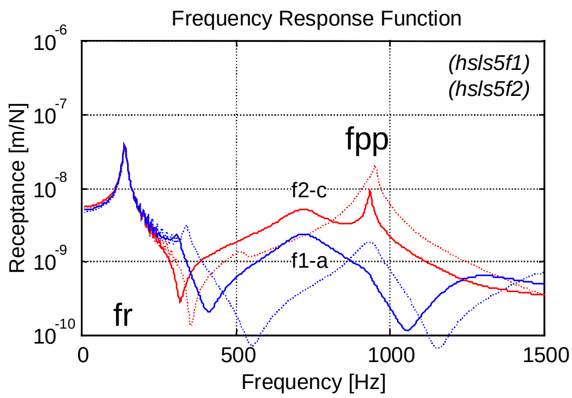

Fig. 16: Simulated FRF with decreased rail pad stiffness(continuous lines) and reference (dotted lines)

All of the above variations - especially applying softer baseplate pads - contribute to lower vertical stiffness of the track (track resilience). Isolation of the track is a common solution in abating vibration transmission and noise nuisance caused by passing railway vehicles. For the train itself, lower vertical stiffness of the track contribute in reducing the (variation in) wheel-rail interaction forces. Durability of the materials, stability and safety are regularly put forward against too soft track fastening systems.

4. Valuable managing information

In the laboratory and in the field, much more railway track structures and components than presented in this paper have been recorded. In many cases, recorded behaviour could be approached with simulations in RAIL by entering only component properties and structural geometry.

In some cases discrepancies between the expected behaviour and the recorded behaviour in the field were found. Then field inspections often showed that there were defects or imperfections at these specific spots. This is valuable information for track managers, in particular for planning maintenance, meeting noise and vibration conditions and most important for supplying sufficient track safety.

5. Conclusions

Testing and analysing methods developed for assessing dynamic behaviour have indicated to be able to contribute to managing rail infrastructure with respect to special operational and environmental conditions. Both methods still have to be streamlined into a suitable system that can support decision making and designing. Until now the examples are too much limited in number to formulate a uniform method, which is however foreseen in the near future.

References

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