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Preface

The work presented in this master thesis has been carried out during the period April-November 2018 at Department of Applied Mechanics at Chalmers University of Technology in Göteborg, with special support from Swedish National Competence Center CHARMEC (CHAlmers Railway MEChanics). I would first like to gratefully acknowledge the efforts of my supervisor, Prof. Thomas Abrahamsson whose guidance knowledge, and unwavering support made this thesis possible. His support was important because, even if I had a lot of freedom to express my ideas, I never felt alone. Thank you because you took care of me.
I thank my co-supervisor Prof. Jens Nielsen, Prof. Roger Lundén and all the people in the department for welcoming me and making me feel part of the CHARMEC group.
I thank my supervisor Prof. Ezio Santagata for the opportunity he offered me.
I would like to thank my colleagues and friends, inside and outside Chalmers. I learned a lot from them and I was always supported by their friendship in challenging and cheerful moments. I would like to thank Michele Maglio, Antonio Settanni, Carolyn Oddy, Pooria Khalili, Eva Eggels and Helena Rivera for the beautiful moments spent together.
I thank my roommate Chouaib for his kindness and my house owner Eva for making me feel at home.
I would like to thank my family. I thank my mother because, thanks to her, I know what it means to support and love. I thank my father for sending me the strength to fight for his own ideas. I thank my brother for always listening to me. I thank my sister because for me she is an example of a strong person. I hope you are proud of me.
I thank Antonio because he always saw my best part. With him everything was and is more beautiful. It's because of him I did it. I dedicate this thesis work to him.

Abstract

There are some phenomena and engineering problems whose complexity is very large. For these, the trustworthiness in simulations and predictions pose a big challenge. The structural response of a railway sleeper is effectively one of these. The complexity is due to different stiffness and material involved, with a large spread in the characterization. A lot of data is required, and the numerical simulations could generate them. Firstly, a selection of which variables are relevant was necessary and an analysis of which of those could be stochastics has been completed. Once the variables are identified, with a mapping procedure, simulations have been realized. In the present work time consuming related to simulations is an issue. Then, some convergence studies and a tentative of simplification have been necessary. The ODE's relative tolerance and the time step has been analyzed. Due to the established tolerance, a numerical noise in the response occurred. In order to simplify, surrogate model could help to build a continue and easier function to be studied. In this thesis work, a polynomial regression was established to obtain a certain smoothness of the response surface.

1. Introduction

Track provides the function to guide the trains. Its composition is very complex because different materials, dimensions and shapes are involved. Consequently, different kinds of stiffness are associated to different types of elements and the wear assumes many complex behaviors. The main elements of a track are the rail, the rail-pads and fastenings, the sleepers and the ballast. The movement of a running train is quite complex. The wheel is a rolling element that rolls and scrolls on the rail. When a train runs, acceleration and deceleration or braking can occur. In addition to this, engine dynamics are to be taken into account and vibrations are very relevant elements. Diversified contact areas between different elements can be associated with different configurations of the train-track system. Consequently, by referring only to the contact areas, stresses can vary a lot. For example, different configuration of Hertz´s ellipse can occur. By going in depth, another type of interaction has to be considered: the ballast-sleeper one. Contact surfaces gradually change and interactions consequently stresses are different again. There is a coexistence of several type of stresses such as shear and dynamics stresses. If one think about the interaction between ballast and sleeper, tangential stresses are also generated. A pressure is transferred from the sleeper to the ballast and from the ballast to the subgrade. Natural ground is below the subgrade and its characterization is not easy to do. Different maintenance conditions are a challenging aspect in engineering judgement and many literature´s works are available, as shown in [19], [20] [21], [22], [23], [24], [26], [25], [27], [28]. The sleeper or tie is a transversal element that guarantees the correct alignment of the track. In the past it was made of wood, nowadays reinforced and pre-stressed concrete elements are used. It interacts with two strongly different materials in composition, with different systems of connection. Fastenings link the rail and the sleeper, with ballast all around it. A rail pad is inserted between the rail and the sleeper. Identification of loads in the sleeper is an issue. Their variation could be impossible to identify. Many models have been studied in literature to describe the supports of a sleeper and its loads. In a structural identification a certain response must be selected. In this thesis work an analysis of the bending moment in the sleeper is built.

Nowadays millions of prestressed and reinforced concrete railway sleepers are installed in rail track every year as shown in [6]. This is an important capital investment by private and public track owners. It is important that the design of sleeper will be based on a rational engineering principle, to avoid a loss of money.

1.1. Probabilistic nature of railway track dynamics

The ballasted track is a complex mechanism. It consists of two major parts: the track superstructure and its substructure. The track superstructure contains rails, rail pads and sleepers, as shown. The sleepers are considered fundamental components of the track superstructure that are used to maintain the gauge between the rails and transmit the wheel/rail contact loads from a passing train down to the uppermost part of the substructure, the ballast bed media. Different and diversified stiffnesses are involved and their interaction is complex. Moreover, dependence on time plays an important role. This is evident on several levels. At first, it is present in the time-dependence of the materials that constitute the ballasted track. But evolution in time does not involve only the materials controlled by man. Below the ballast there is natural soil subjected to a strong variation in time, as shown in [17]. On the figure below, the problems related to the ballasted track system are shown. In a picture of the track in a certain time, it has been observed that there is a strong density reduction along the sleeper-ballast interface.

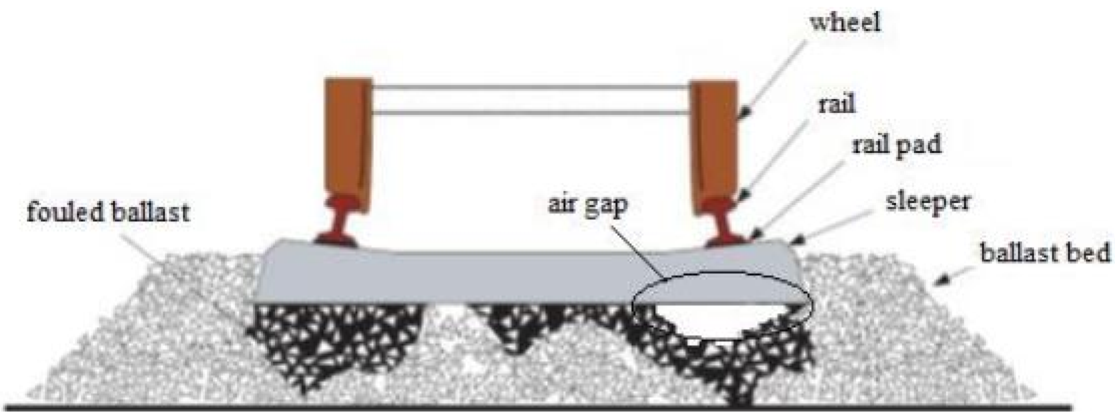


Figure 2: Significant variation of ballast density along sleeper-ballast interface.

Currently in a lot of countries, concrete sleepers are still designed according to a deterministic method, called 'permissible stress design' (e.g. AS1085.14-2009 (Standards Australia, 2009a), AREMA (2010)).

In the last decades the use of codes was developed. In these codes, as shown in [33] a limit state method is used, and it is more effective and economical. Many sleepers are replaced only because of non-design factors such as a serious damage due to derailment or inappropriate materials in the concrete mix. As mentioned above, for economical reason a stochastic and probabilistic approach must be considered in order to take into account the variability of element strengths and of applied loads.
A probabilistic analysis is performed to underline the spread in track properties. For a more in-depth analysis refer to appendix A.

The dynamics of train passage are a fundamental aspect. Trains are often not all the same and have characteristics that change over time. The speed of the train influences the vibrations to which the system is subjected. The different configurations of the alignment lead, for example in a curve, to stress the rail transversely. The influence of out-of-roundness of a wheel on the dynamic train/track interaction is often considerable. The state of maintenance is of vital importance in the railways. Monitoring related to the identification of the state of maintenance is necessary. In figures 9, 10, 11, 12 some images related to the damage detected by situ tests are shown. The state of maintenance plays a considerable role and the different models of train and their composition have a fundamental importance. For this thesis work, some data from the Swedish railroad administration Trafikverket have been used, to underline the variability and then the severity of railway´s distresses. Trafikverket provides some situ tests such as the OFP, the non-destructive testing. Common imperfections are irregularities on the running surfaces of a rail and wheel and deficiencies in the support of the track structure. For a more in-depth analysis refer to appendix A.

The variability of traffic loads is very large nowadays. Different speeds are related to the different type of trains. A lower speed and higher speed are associated to freight train and passengers train, respectively. Homogenization in railway´s traffic is a problem. Speed is a variable whose complexity should require an entire model to be studied. In this thesis work, a study on topic of speed will be not considered. For the sake of completeness, a brief literature review has been defined and it is reported in the reference of this work. However, a distinction between different speeds involved in track dynamics is necessary.

Multiple speeds are involved, or, more precisely, different components of the speed. Firstly, if one focuses on the geometry in a large scale, the horizontal alignment is fundamental. It is known that by crossing different horizontal element such as straight and curve the contact area between the train and the rail changes and the dynamics are different in the transition. Transversal loads are generated due to centripetal acceleration. A transversal speed has to be considered in the study of dynamics in railway´s problems. A longitudinal speed is associated to the train´s axis and a transversal speed in his orthogonal direction. In this thesis work a certain observation´s period is established and speed is a variable to be analyzed. Even if in some literature´s work, such as Antulor (1991), speed is considered to be not influent, in this work it is assumed to be relevant. Speed is taken into account as a cause of bending moment in the sleeper. Due to this we focus on the cumulative effect of the speed. We expect to find that a speed´s increment is linked with higher stresses in the sleeper, due to the fact that the train is occupying the track and generates bending moment.

In the present thesis work, therefore, the variability associated with the speed parameter has been modeled through probabilistic mapping methodologies with reference to the longitudinal speed, omitting the transversal component. As a general effect, dynamics phenomena have a higher relevance with increasing speed. This effect is amplified when one considers the presence of irregularities. Impact of the corners of a wheel-flat´s length on the rail is higher with increasing speed. For this purpose, a section of a commercial, heavy-haul, narrow-gauge railway track in Central Queensland, Australia, was selected for installation of a device known as a wheel impact detector. Nearly 3 million readings were taken of the forces applied by train wheels to the rails over a period of 12 months. Some of the results of those infield tests are described below. The interaction is not only static but above all dynamic between the wheel and the track. Two types of loads have been considered in [6] :

- Gravity loads. For a railway sleeper, the permanent load it sustains is its own self-weight and the weight of the rails it supports, but that is only about 0.3% of the weight of a loaded wagon running over the track, and so is not significant. The more important gravity load carried by sleepers is the weight force applied as each individual axle passes quickly over a sleeper. Although these are gravity loads they should be thought of as multiple transient forces that are usually called ‘quasi-static’ loads in railway parlance. The distribution of the wagon gravity loads per axle measured at the test site is shown in Figure 1. In the trains passing over the test site there were four axles per wagon, about 100 wagons per train and 10 fully loaded trains per day, giving about 1.5 million transient loads from full wagons applied to a sleeper per year in Figure 3. maximum axle loads for full wagons were well above 28 t. By converting the results in the Figure 4, one could observe the distribution is approximately normal with a mean force at one wheel-rail interface of 128 kN and standard deviation of 13 kN.

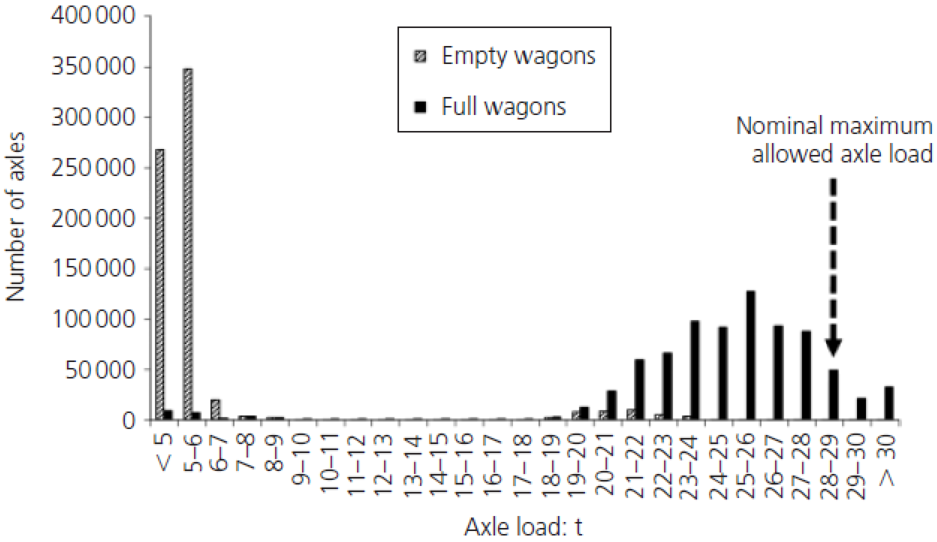


Figure 3: Distribution of wagon weight transmitted through axles, 2005–2006.

-Dynamic loads. When the steel wheels on a train become worn asymmetrically they can become 'out-of-round' and can even develop small flat spots on the wheel tread. These imperfections strike the head of the rail each time the wheel rotates and if they are severe enough they can generate very large impact forces to the head of the rail which get transmitted down into a sleeper beneath. These impact forces are quite different from the gravity forces that are caused by the vehicle mass; impact forces were measured at the test site which were just as large from empty wagons as from full ones. The wheel impact detector at the test site measured these forces, and the distribution of wheel impact forces over the 12 month period of testing is shown in Figure 2. These data show only the dynamic force over and above the static wheel load, that is, the incremental impact force, and only those impact forces of significance, defined as impact forces larger than 50 kN. The diagram is derived from data presented in Leong (2007) but adjusted to allow for the fact that the detector measured the impact forces occurring over a distance along the rail head of 3 m or more, but a given sleeper experiences full impact only if the impact occurs on the rail head above that sleeper. The distribution in Figure 2 is not of a normal shape but is heavily skewed like many natural stochastic processes such as wind speeds, rainfall and earthquakes.

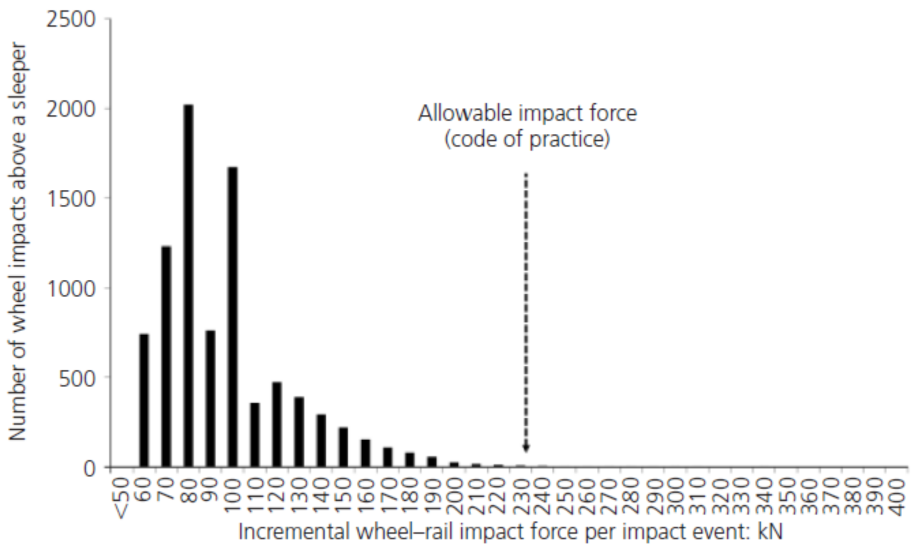


Figure 4: Distribution of incremental impact force transmitted through wheels, all wagons - 2005–2006.

The dynamic effects related to the wheel-flat length will be discussed below. A statistical study is reported on this interaction. As previously seen, the presence of defects in the surface of the rolling wheel gives the system a dynamic stress. Since this is a rotating element, one expects to encounter a periodic problem. Specifically, it is in fact interesting to observe the presence of defects in combination with different speeds of the rolling wheel. In fact, we know that in a periodic motion, which can reasonably be considered a rolling body, the velocity can be distinguished into several components. in general, without going into detail, it is useful to keep the impact speed of the wheel-flat edge on the track, even if in reality there should be considered jerky motions.

In [30] several simulations conditions are selected to analyze the W-R interactions. A variation of the flat size (L) was established at different running speeds in km/h. Results are reported below.

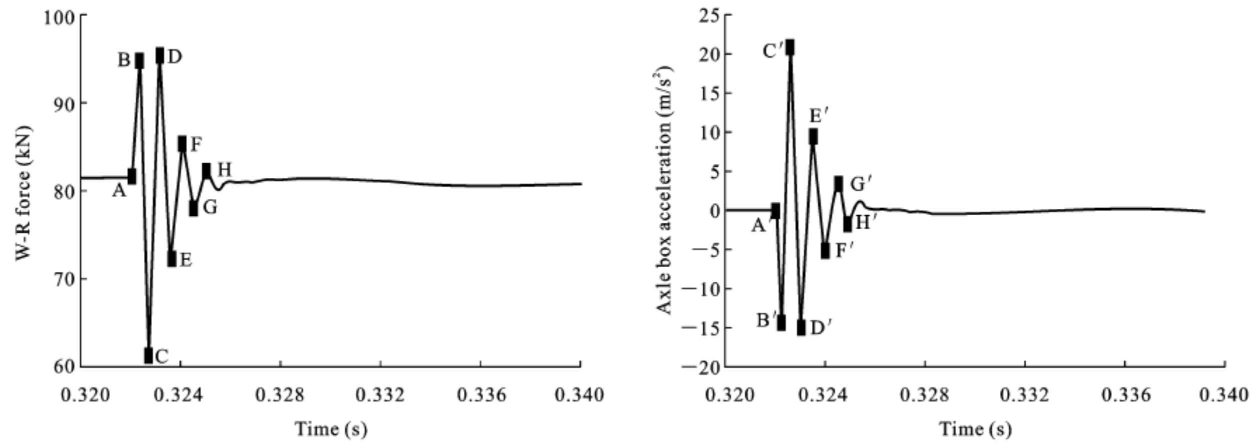


Figure 5: Time histories of W-R force and axle box acceleration (V=50 km/h, L=10 mm).

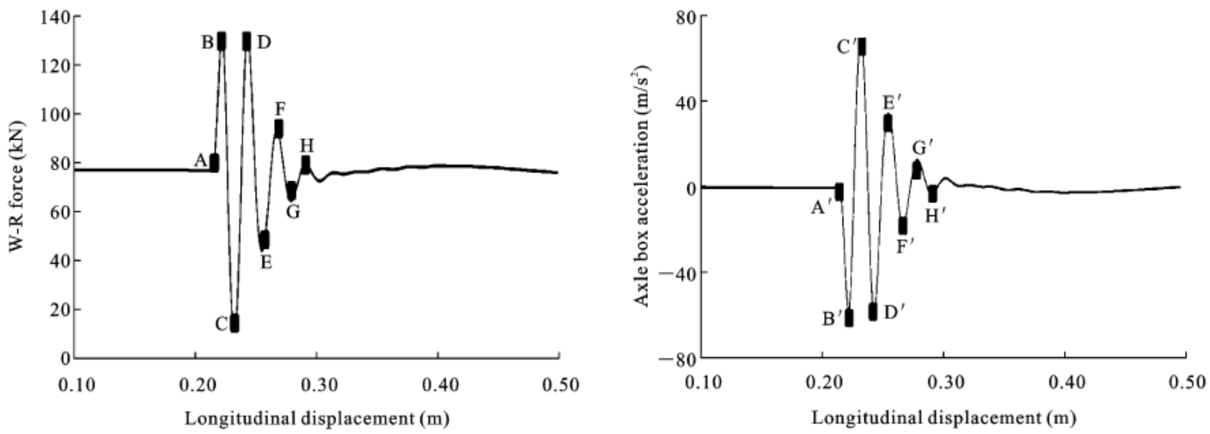


Figure 6: Time histories of W-R force and axle box acceleration (V=90 km/h, L=20 mm).

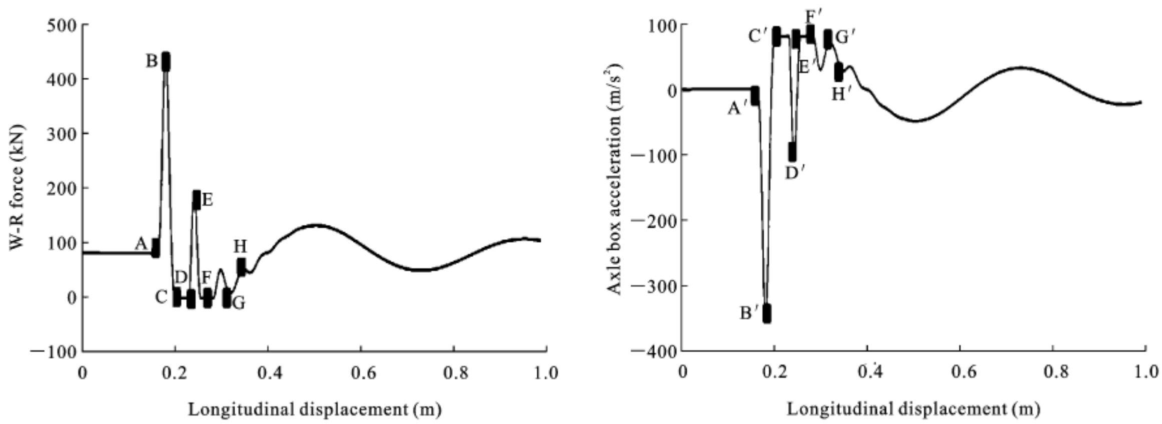


Figure 7: Time histories of W-R force and axle box acceleration (V=150 km/h, L=70 mm).

A loss of contact is unavoidable. For a certain time the wheel 'flies' and then hits the rail. In the study an analysis is also developed. It has been observed that loss of W-R contact easily occurs when the running speed of vehicle is high and the wheel flat size is big. The frequency of W-R shock caused by small flat size at high speed is higher. FSWT is a new time-frequency analysis method. It is used to analyze the time-frequency characteristics and realize the location of time-frequency characteristics along the circumference through the combination of the time-frequency characteristic, running speed and wheel radius.

The multiple energy peaks of axle box accelerations would appear when loss of W-R contact occurs, which provide a powerful tool to detect W-R contact situation.

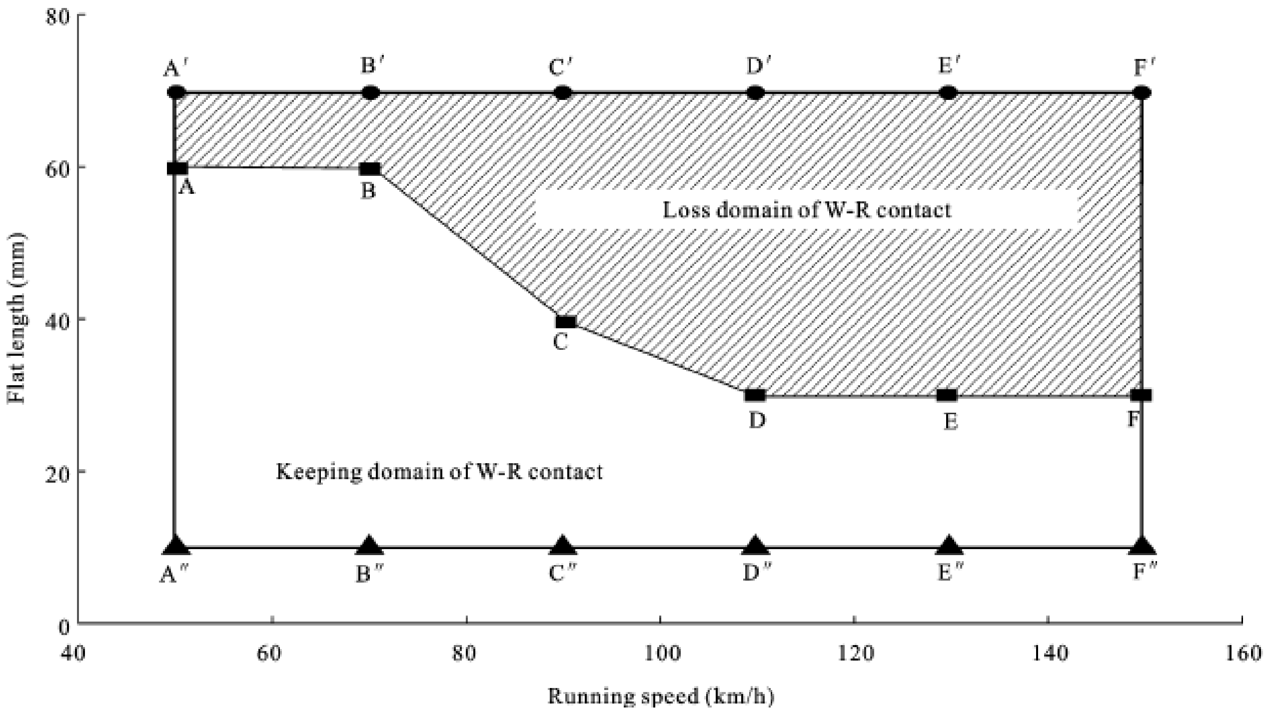


Figure 8: Statistical results of W-R contact situation.

In many engineering problems, the analysis of a probabilistic distribution leads in an assumption. As an example, the distribution of a certain probability density function in material´s science identifies some design values, such as the characteristic strength. Simulations are performed in this work. If in the inference´s problems typical values are derived, when one wants build a simulation an opposite path is shown.

By establishing a lower value and an upper value in the uniform probability density function, a variability of some nominal parameters could be defined. The uniformity of the distribution gives randomness to a certain phenomenon. This given randomness allows to make important assumptions on the physical phenomenon. As mentioned above dynamics effects are taken into account in this analysis. Wheel-flat corners, we know, can impact the rail and impulse could be generated. Given this randomness, one can assume that the impulse is given in the sleeper of interest. In practical terms, once the variability of the speed is given, by properly selecting an integration time in the solver, this assumption can be realized.

Distressess in railways

The purpose of using non-destructive testing (OFP) in Trafikverket's track is to detect defects and damage in rails and rail components at an early stage, thus avoiding crimes and traffic-disturbing situations, as well as being used as a basis for planning maintenance measures in the longer term as shown in [30] [31] [32].

In the following figures some rail defects and distresses are shown (images by Trafikverket´s documents, for the nomenclature see appendix C.).

Figure 9: The error is verified and marked with white color on the outside of the rail.

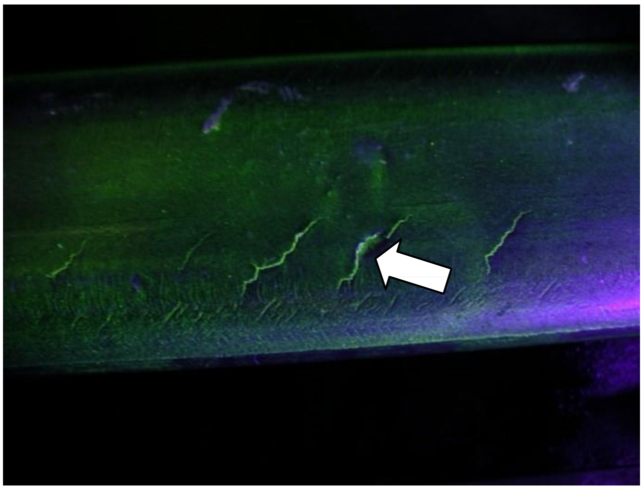


Figure 10: Sparse cracks (Spalling).

Figure 11: Damage due to pressure after a long time in the track.

As reported in [29] heavier trains and higher speeds increase the influence of imperfections in vehicles and tracks on the dynamic interaction between the two. Large dynamic loads may be excited causing significant damage to both track and vehicle. In high frequency vibration isolated defects such as a large wheel flat or a badly aligned rail-joint can occur, while for examples loss of ballast under a single sleeper mostly will affect the low frequency response of the track. The dominating frequency depends wavelength of the irregularity and the speed of the train.

During the impact of the traffic, the rail head is worn or deformed to a greater or lesser extent. The deviations from the original rail profile may consist of height wear, side wear or deformation. In addition, rusting and surface damage can occur in the rails, as shown in [14], [15].

Height wear is the vertical height decrease of the rail head. It shall be measured in the center line of the original rail profile. Side wear is the profile deviation of the rake head side. This wear is measured horizontally 14 mm below the actual rail surface of the worn rails.

Height and side wear may occur at the same time. Their combined impact on the mechanical bearing capacity of the rails can be expressed through the connection:

$$H = h + s / 2$$

Where: H = is termed comparable height wear h = height wear

s = side wear ($s = s1 + s2$ for double sided head wear).

Vertical dynamic interaction between train´s wheel and rail is strongly influenced by the surface defects. Between the rail and the wheel static and dynamic interactions take place. The combination between speed and surface defects could be fatal. The wheelflat´s corners can generate an impulse load whith large spread in vibrations. Different frequencies of vibrations are associated once speed and wheelflat´s length have been identified. In literature and in many current research projects the response related to the W-R system is a very complex subject on which research is investing a lot. In next paragraphs an overvew of literature about this specific aspects is reported.

Figure 12: Courtesy from 'Image analysis of defects of railway wheels: a challenge for mathematicians', Elena Kabo CHARMEC / Caran

1.2 Aim and limitation of the thesis

As mentioned above, due to the complexity of the phenomena related to the study of railway system, in this thesis work, an analysis of the response is necessary. The response could be associated to many aspects in a track, whose involve microscopic phenomena such as material to be used up to more general problems such as a re-alignment of the rail. Focusing on the response is important to underline the behaviour in order to make back-calculations, before-after analysis or in a pre-design stage. In railways maintenances' plans there are also applications where identify the response of the system is fundamental. Murray and Leong (2009) identified three limit states for concrete sleeper namely strength, serviceability and fatigue. The prediction of an accurate and simple response function in a little time step and its decrement could also lead in a review of safety factors, as a safety´s measure. The aim of this thesis work then is a study of a model of the response function related to the bending moment in a sleeper. The optimization of the response could be in contrast with time-consuming purposes.

The methodology consists, firstly, in a selection of the variables of interest, which is strengthened by a probabilistic analysis of their characterization, in term of spread in properties. Numerical simulations can help to obtain a lot of data, in addition to in-situ tests. Finally, a model is built to reproduce the response and it must perform train simulations and, on the other hand, must be simple to be studied. A regression model is considered, then, to obtain a simplification and some convergence´s studies are performed to optimize the analysis in terms of time-saving.

2. Simulation of track dynamics

At this stage it is necessary to refer to a certain response function. For this purpose, we talk about performance function. Response function methodology (RSM) is considered. RSM is a collection of mathematical and statistical techniques for empirical model building, with the objective of to optimize a response (output variable) which is influenced by several independent variable (input variables). In this thesis work we focus on the bending moment in the railway sleeper. For the reasons previously mentioned it is known that the performance function depends on many parameters. The selection and the characterization of these has been done before. It is obvious that we need to look for a simplification that in this phase happens through a statistical mapping procedure.

As shown in the previous chapters, the modeling of the response of a sleeper during the train´s passage is therefore a highly complex phenomenon. Simplification is strongly needed. In this thesis work a numerical analysis is considered. Firstly, an approximation should be made. The approximation is expressed through engineering or design choices, through assumptions, or a-posteriori evaluations, as an analysis of the results. The approximation of the numerical modeling of the simulations has been analyzed. By focusing on a numerical approach, we analyze the outputs of the response function. First of all, it is necessary to define the meaning of the approximation by the mathematical point of view in the simulation of complex phenomena.

The application´s purposes or intended use defines the parameters to be analyzed. More precisely, the variables that influence the response function have been defined. Firstly, if one considers the approximation in mathematical terms, a selection of relevant items is necessary. By the mathematical point of view, the identification of the variables involves a reduction in terms of the size of the domain to which they belong.

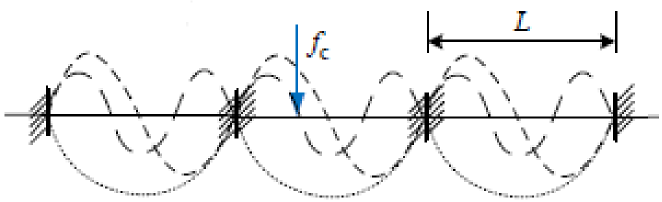
As expressed in [10] the simulation of complex phenomena requires the approximation of a function of infinite domain to one whose domain has dimension n. Clearly, with the term infinitive function, mainly by the engineering point of view, we refer to a function in which the variables are multiple or whose complexity is very high. Due to the aspects mentioned above the complexity of the response function associated to the sleeper can be associated to a f_∞.

The choice of the domain size of the approximate function was made previously. Now by considering the values assumed by the function and try to establish a numerical analysis. It is known that the reduction of the domain from infinity to finite is given by a series of operations whose effect is linked to the truncation error. In fact, if the number of decimal places associated with a certain value of f were infinite, the value would be the exact one. Therefore, when a finite domain function, given by an approximation f to finite precision evaluations, is coupled with a certain tolerance, computational noise occurs.

From previous studies it is known the model through which it is possible to complete the simulation model of the passage of the train.

2.1 The DIFF- train track interaction model

A 6 meter long section of track has been analysed with 10 equally spaced 60 cm sleepers. For



dynamic problems, the local system is excited by external loads and the inertia of the global system, thus it requires to be described in elements adjacent to the loaded one. The rail is considered as a built-in beam and the sleeper of interest is the 5th one in the middle. Referring to the [34] model used in the optimization is reported below.

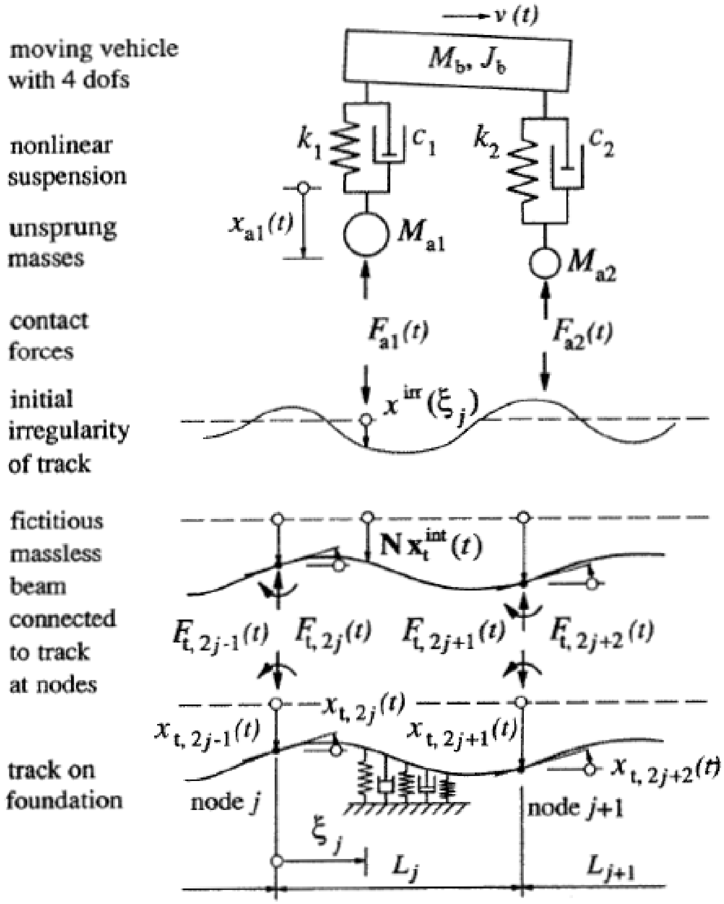


Figure 13: Physical model

Vertical motion of moving vehicle described by two interfacial dofs X_{a1} and X_{a2} and two non-interfacial dofs X_{b1} and X_{b2} associated with inertias M_{a1}, M_{a2}, M_b and J_b, respectively. Linear or non-linear massless suspension with stiffnesses k_1 and k_2 and dampings c_1 and c_2. Part of finite element model of track structure including one element model of the track structure including one element j of lenght Lj between chosen nodes j and j+1. Nodal translations $x_{t,2j-1}$ and $x_{t,2j+1}$ and nodal rotations $x_{t,2j}$ and $x_{t,2j+2}$ of track. Fictitious load-transmitting uniform massless beam connetted to track at nodes. Current location of M_{a1} on massless beam element number j determined by local co-ordinate connected to track at nodes. Current location of M_{a1} on massless beam element number j determined by local co-ordinate ξ_j.

Input file

The optDiff code was developed in [1] and [2] in the competence centre CHARMEC [3]. The user specify the stochastic parameters here. That includes the density function types (here both are uniform). Any number of parameters are allowed by adding rows to the sheet, however more parameters means exponential growth of calculation time.

	A	B	C	D	E	F	G
1	DIFF - Stochastic parameters						
2	Name	Nominal	Lower bnd	Upper bnd	Mean	Std dev	Type
3	Ballast stiffness mult	1,0000E+00	5,00E-01	2,00E+00	1,00E+00	1,50E-01	uniform
4	Pad stiffness mult	1	0,5	2	1	0,15	uniform
5							
6	Hint: Make formula using nominal cell data for data on "Solver and Train Data" and "Track Data" panels						

... Track Data | Sleeper Data | **Stochastic Parameters** | Design Parameters | Model Re

The user specify the design parameters here to their nominal value. Any number of variables are allowed by adding rows to the sheet, however more variables means exponential growth of calculation time.

	A	B	C
1	DIFF - Design parameters		
2	Name	Value	
3	Young´s modulus	4,00E+10	
4			
5	Hint: Make formula using value cell data for data on "Solver and Train Data" and "Track Data" panels		

... Track Data | Sleeper Data | Stochastic Parameters | **Design Parameters** | Model Reduction | Pc

Linking of stochastic and design variables to Diff input

The linking of variables to Diff input are made via the Excel sheets. The formulas are updated by the running optDiff for the variables. The following illustrates how the stochastic variable "Pad stiffness mult" (user can give arbitrary name) is linked to the Diff input for pad stiffness.

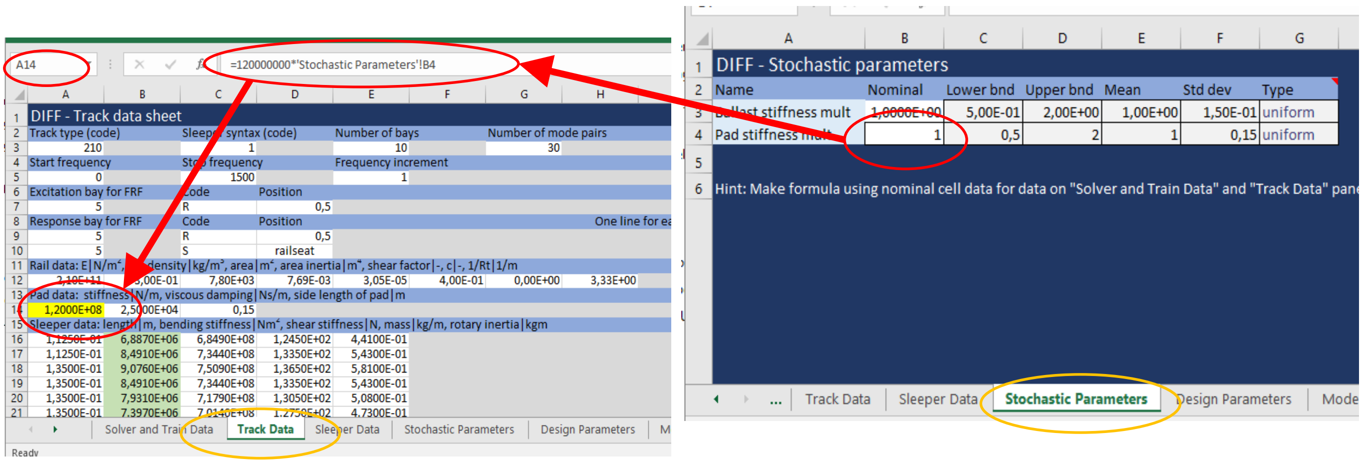
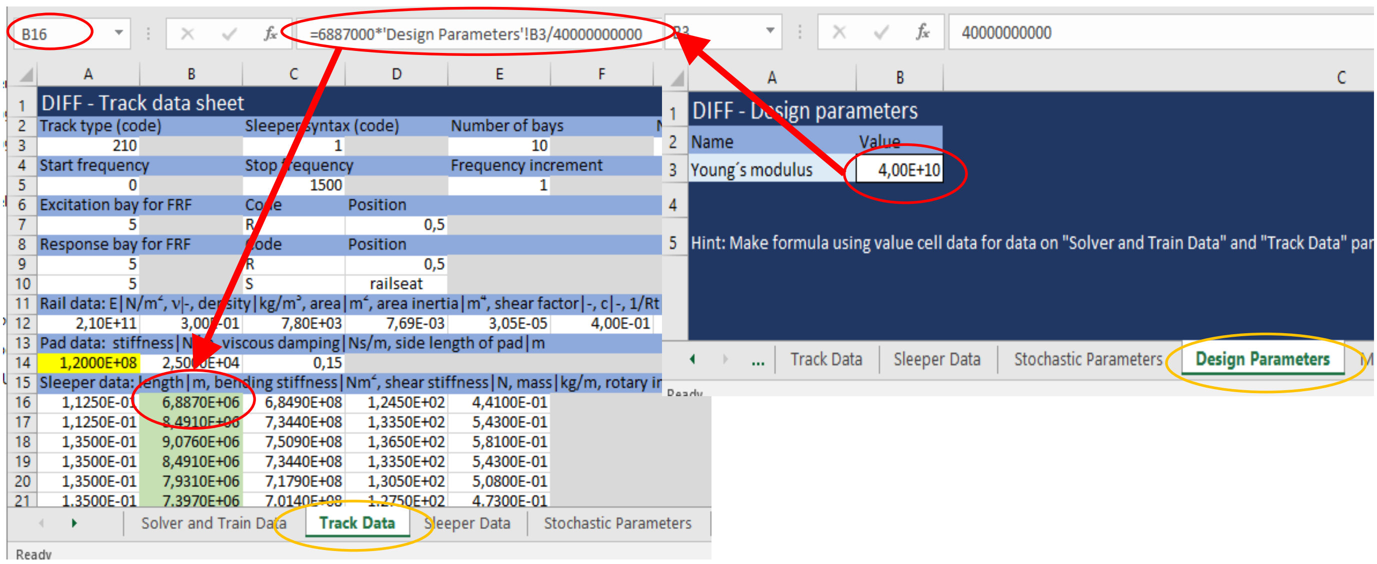


Illustration of how stochastic parameter "Pad stiffness mult" in cell B4 of sheet "Stochastic Parameters" is linked by formula to pad stiffness data for Diff in cell A14 of sheet "Track Data".

and the following illustrates how the design variable "Young's modulus" (user can give arbitrary name) is linked to sleeper bending stiffness. Note that Excel provides a very flexible means of linking stochastic and design variables to Diff input.



-Illustration of how design variable "Young's modulus" in cell B3 of sheet "Design Parameters" is linked by formula to pad sleeper bending stiffness data for Diff in cell B16 of sheet "Track Data".-

Performance function view

An example of generic performance function is shown below. It is a bi-dimensional visualization in the space of parameters U1 and U2 (derived by mapping) of a complex performance function, in which several parameters are involved. In this thesis work then, we will refer to a simplified visualization of the performance function, but we must take into account that is for reasons of representation. Actually, a complete vision of the performance function involves a multidimensional space.

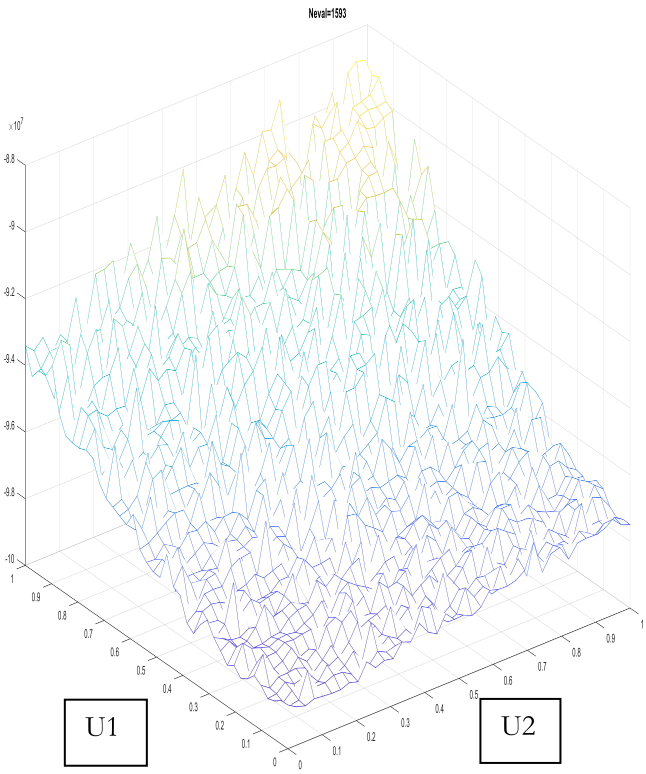


Figure 14: Performance function view

Preliminary study for the ODE solver. Convergence´s studies.

Numerical methods for ordinary differential equations are methods used to find numerical approximations to the solutions of ordinary differential equations (ODEs). Their use is also known as "numerical integration", although this term is sometimes taken to mean the computation of integrals. Numerical methods for solving first-order IVPs often fall into one of two large categories: linear multistep methods, or **Runge-Kutta methods**.

Runge-Kutta methods are used. In simple terms in the RK methods the y_{n+1} is the RK-J approximation of $y(t_{n+1})$ and the next value (y_{n+1}) is determined by the present value (y_n) plus the J weighted elements of J increments.

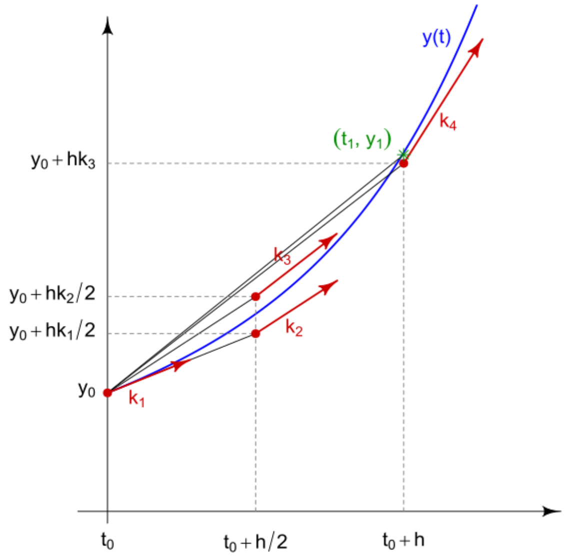


Figure 15: Runge-kutta method

Therefore at this stage it was necessary to make convergence studies in terms of relative tolerance and time step. More precisely, setting a tolerance means calculating the error between two different orders of approximation of the above methods. Through a MATLAB code it has been possible to calculate the values of the bending moment by varying the values of some quantities that influence it. In the following tables convergence studies related to relative tolerance and time step are reported.

Rel. tolerance [-]	Mr [KNm]
$97 \cdot 10^{-6}$	415,260
$195 \cdot 10^{-6}$	415,260
$391 \cdot 10^{-6}$	414,710
$781 \cdot 10^{-6}$	415,210
0,0016	415,230
0,0031	413,580
0,0063	412,440
0,0125	414,210
0,0250	413,410
0,0500	426,119
0,1000	404,490

Table 4: Results from convergence's study for the relative tolerance of the ODE's solver

Time step [s]	Mr [kNm]
1,000E-02	176,750
5,000E-03	185,690
2,500E-03	177,020
1,250E-03	188,580
6,250E-04	217,480
3,125E-04	413,570
1,563E-04	414,870
7,813E-05	414,730
3,906E-05	420,280
1,953E-05	423,050
9,766E-06	422,290
4,883E-06	420,910
2,441E-06	422,480
1,221E-06	422,340

Table 5: Results from convergence's study for the time step of the ODE's solver

It is possible to observe how for the relative tolerance 0,001 leads to a good approximation, due to the fact that the computed values do not change. On the other hand, 1,00E-05 is a good value for the time step.

2.2 Numerical scatter in simulation results

OptDiff´s performs a simulation and it is obtained by means of statistical tools, first of all the mapping. As mentioned above, the performance function is a multi-variable function, whose the entire visualization is not possible and simplification is necessary. It is therefore fundamental to specify the methodology adopted to obtain the results. This methodology consists of:

choice of a set of the stochastic parameters;
choice of a lower bound multiplier and a upper bound multiplier in the assigned pdf u;
choice of a number of discrete points to be plotted of the U pdf;
run different simulations;
representation of post-processing data in terms of maximum bending moment.

Four variables have been analyzed, as a result of mapping process:

Ballast stiffness
Pad stiffness
Train speed
Wheelflat length

The formula to compute the track input data is reported below:

$$K_{PARAMETER} = \beta_i \times K_{PARAMETER,0}$$

Where:

$K_{PARAMETER}$ is a stochastic parameter,

$K_{PARAMETER,0}$ is the nominal parameter,

β_i is a stochastic multiplier with the same distribution type as $K_{PARAMETER}$; it is a function of U, where U is a stochastic standard uniform variable.

And β_i is obtained as:

$$\beta_i = U\left(\overline{\beta} - \underline{\beta}\right) + \underline{\beta}$$

Where:

$\overline{\beta}$ is the upper value,

$\underline{\beta}$ is the lower value.

By establishing an upper bound value and a lower bound value it is possible to fix the value of U. In this way it is possible to generate a lot of random data useful to simulate the train passage and build the response function.

In the code a mapping is performed.

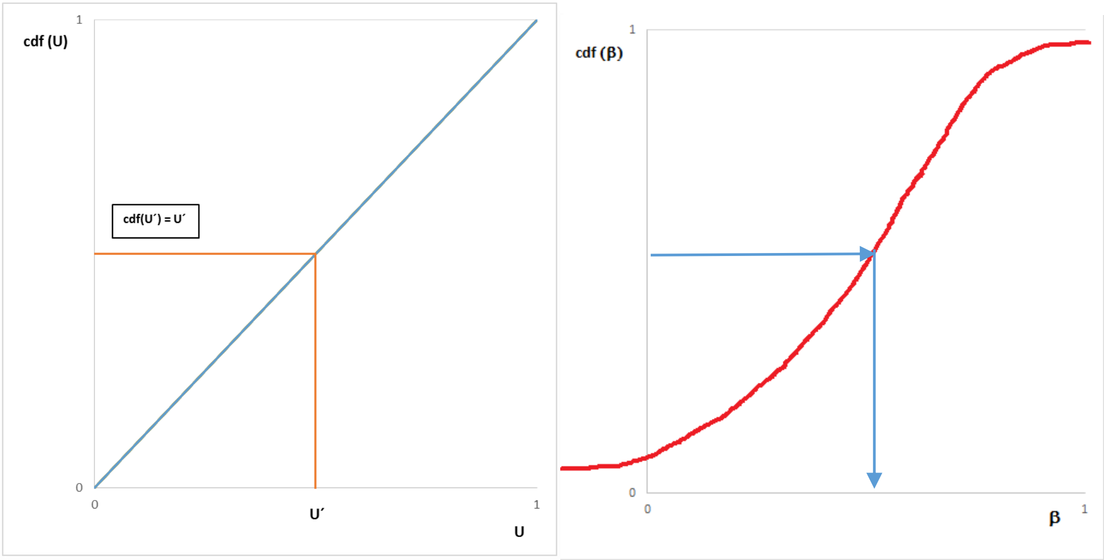


Figure 16: Mapping procedure

β follows a certain distribution. Since the cumulative density function is always positive, it is possible to fix a certain value in the cdf(U) and to obtain the certain value of β. This procedure allows to map U´ to $\beta'(U')$.

In the following table choosen values of lower bound and upper bound are reported.

DIFF - Stochastic parameters						
Name	Nominal	Lower bnd	Upper bnd	Mean	Std dev	Type
Ballast stiffness mult	1,0000E+00	5,00E-01	2,00E+00			uniform
Pad stiffness mult	1,0000E+00	5,00E-01	2,00E+00			uniform
Speed mult	1,0000E+00	5,00E-01	2,00E+00			uniform
Wheelflat mult	1	0,1	1			uniform

Table 6: Stochastic parameters

In figures below results of performance function are shown. They are obtained by fixing β at unit for three parameters and by varying β for the choosen parameter. Operatively, a number of different interest point has been chosen by selecting a step of 1/40 from 0 to 1. Then, perturbations around them has been realized by selecting a 10^{-6} truncation error in the code. A set of `samples` or scatter of numerical observations given precisely by finite precision is obtained.

One can observe how the manifestation of the numerical noise is very different according to the different 2-d visualizations of the performance function. The analysis can be conducted with two different approaches, referring to the variation range of the solution and the numerical noise distribution for each group of scatter points associated with the perturbation.

In general it is noted that for the ballast the solution has a range of variability equal to 0.4 *10 -5. For each group of observations the numerical noise distribution is pretty extensive. The result associated to the pad and to the speed are more different respect to the ballast, since numerical noise distribution covers a less extended range. This suggests a different sensitivity of the simulation model to the parameters involved. In the following paragraphs a statistical view of the distribution of numerical scatter is reported.

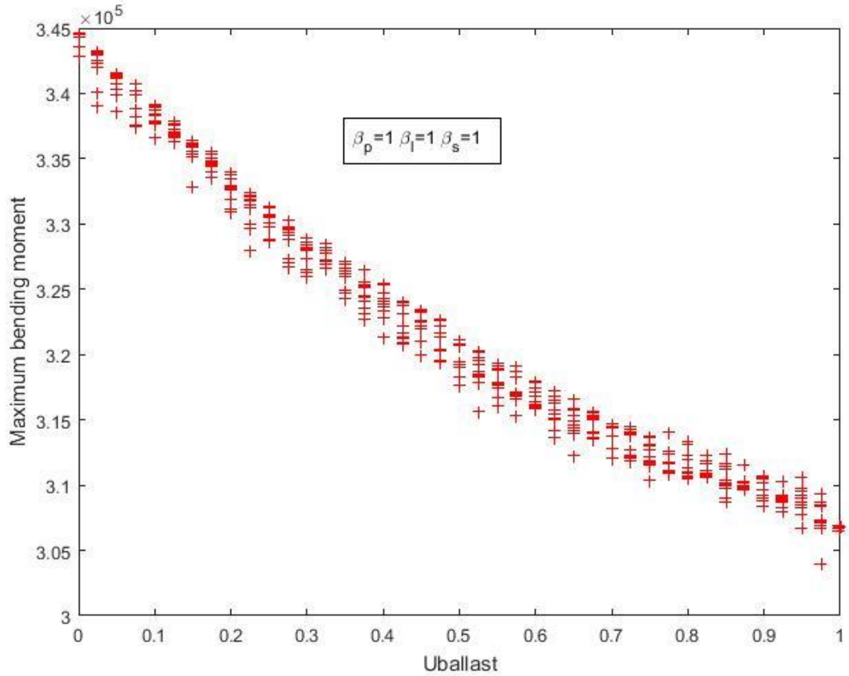


Figure 17: Numerical scatter for the ballat

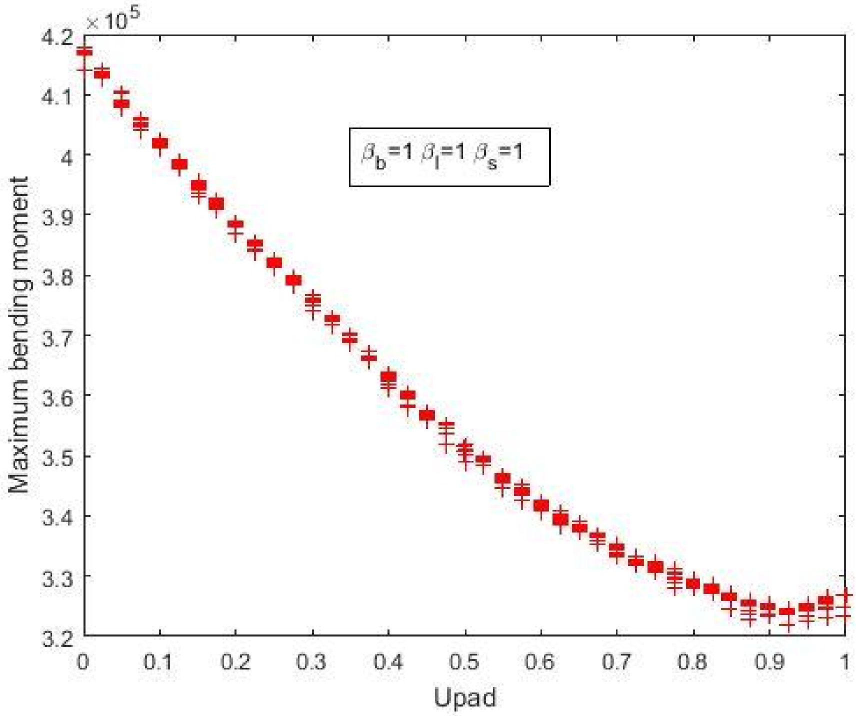


Figure 18: Numerical scatter for the pad´s stiffness

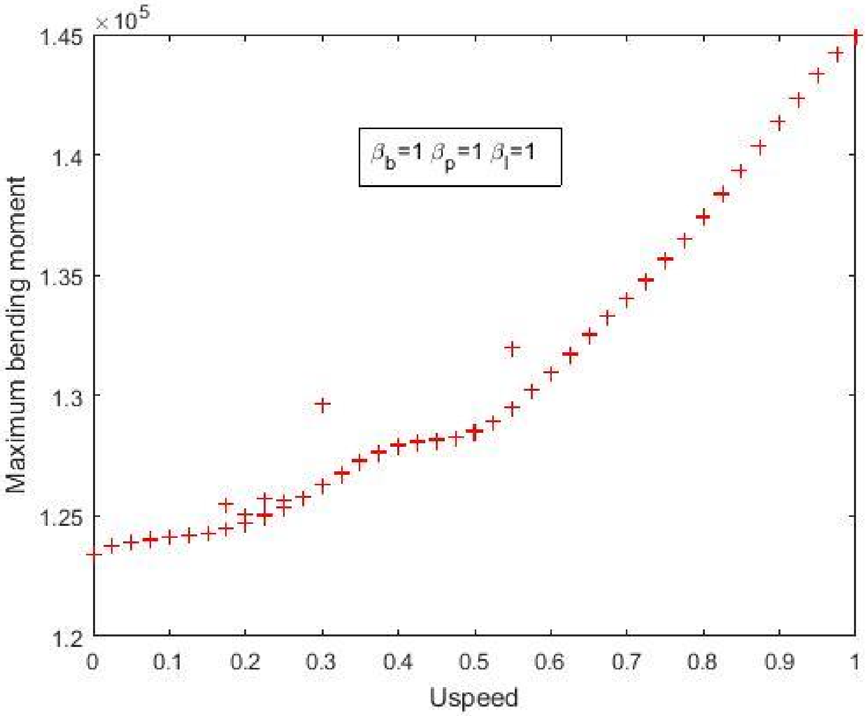


Figure 19: Numerical scatter for the speed

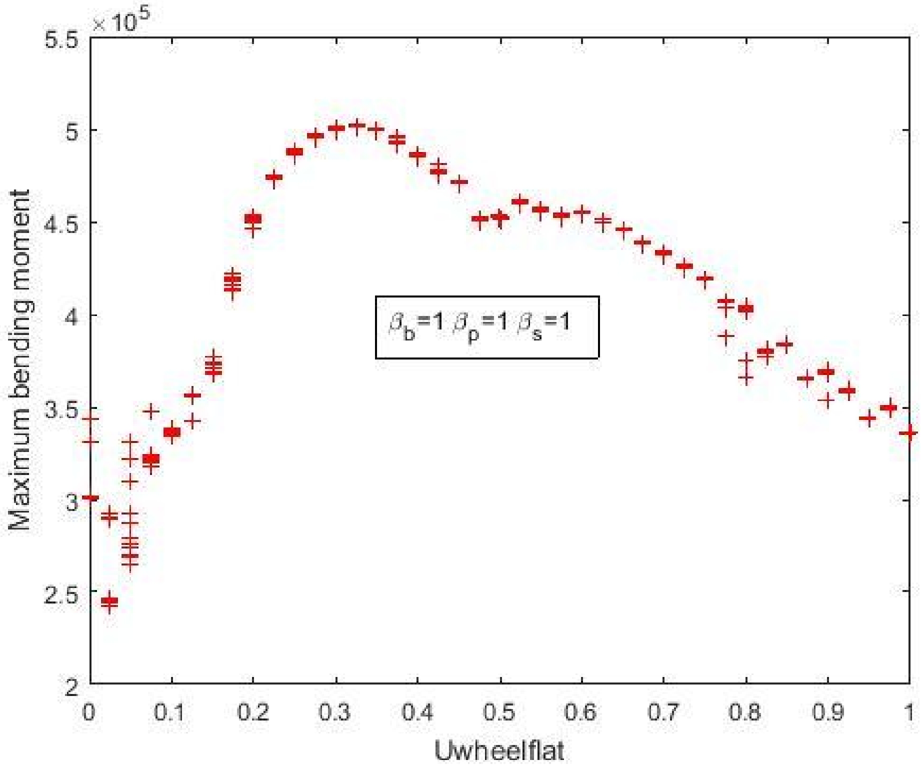


Figure 20: Numerical scatter for the wheelflat

3. Surrogate models

In the present work an optimization´s process is an issue. The optimization by itself implies, generally, a lot of parameters such as reduction of costs, time and resources. Aspects related to economy and resources are not analyzed. In this thesis´s work the optimization is expressed in terms of time consumption and efficiency. This, however, in a probabilistic design approach, could lead to a loss of accuracy. Therefore, a surrogate model with the best possible accuracy is needed. Furthermore, to find a certain smoothness of the model is important in order to eliminate random noise due to a certain precision.

Indeed, the systematic exploitation of surrogate models seems to be the most promising approach to reduce both the influence of noise and the number of function evaluations. As shown in [9], any surrogate model one could construct in the vicinity of current guess does not reproduce the original data set exactly, so an approximation is necessary, as a result of the analyst's a priori knowledge of the model considered. The capabilities to control the smoothness properties of the model is fundamental in a useful modeling. Continuity is a good aim as well. With a continuous function the derivative can be computed, with a lot of simplifications. Furthermore, the continuous surrogate model could greatly reduce the noise present in data. In order to have more regularity in the performance function a surrogate model is necessary.

A polynomial regression was established. The fundamental hypothesis in the code is that between samples function behaves quadratic. The quadratic function is locally a good approximation. This is due to the need of a balance between time consuming and accuracy. The polynomial regression can be made to the mean value or to the real values. It was necessary to split the data into two sets. One to perform the calculation and one to validate the model. Consequently, the errors have been computed. Different methodologies to analyze the smoothness are present in literature. In the following paragraph one is shown.

3.1 Model calibration and validation

It is now necessary to think of a way to identify the polynomial order. A series of steps are therefore necessary. It is known that in machine learning algorithms must be studied properly. In fact, overfitting can occur. The phenomenon of overfitting has a connection with the layout of outliers. Outliers are those points that are very far from the average and median. In order to achieve this, two quantities will be compared. Once the data set has been split into two equal parts, the two curves have been studied: one related to the training error and the other related to the validation error.

A general procedure is reported. As mentioned above surrogate models are necessary to identify unreliable data or outliers. Unreliable data are identifiable if one computes the mean values. By simply observing the distribution of the data plotting it is possible to see unrealistic data. These are related maybe to measure´s biases. By computing the mean values and the box-plot of data it is possible to detect them immediately. The mean and the box plot are two simple models. So actually the procedure explained below is a chain of models that are linked one to each other. The methodology is based to a global minimum in the validation error´s curve. Once the global minimum is defined, the polynomial´s order is identified. Obviously if one refers to the computation´s error with increasing the polynomial order, a reduction is achieved. The validation error, on the other hand, behaves differently and a minimum is to be identified.

The procedure to choose a polynomial order is reported:

- **Plot the data, the mean values and the box-plot to identify the unreliable data graphically;**
- **Build a polynomial regression model with an increasing order and compute the values with the first half of data set;**
- **Compute the values with the other splitted data;**
- **Compute the errors related to the two data set and find the global minimum.**

3.2 Single –variable polynomial models

For each group of observations, the mean value has been computed and the results have been represented by a curve of red squares. In the following step the box plot for each group of observations was overlapped. It is known that the box plot contains the median. The distance between the mean and the median indicates how much a certain distribution is different from the normal one. It is known that in the normal distribution the mean and the median coincide.

With a green line the regression of order n is indicated and with a black line and a red line the regressions with of order n+1 and a the regression made with of order n - 1 are indicated, respectively.

Once the polynomial regression studies performed through the local minimum of the Euclidean norm (norm command of Matlab) are carried out.

3.2.1 Observation from curve fitting

Surrogate model´s smoothness of the ballast´s stiffness

For ballast´s stiffness results are shown below. Smoothness´s studies lead to a 2-order polynomial, since the norm has a global minimum.

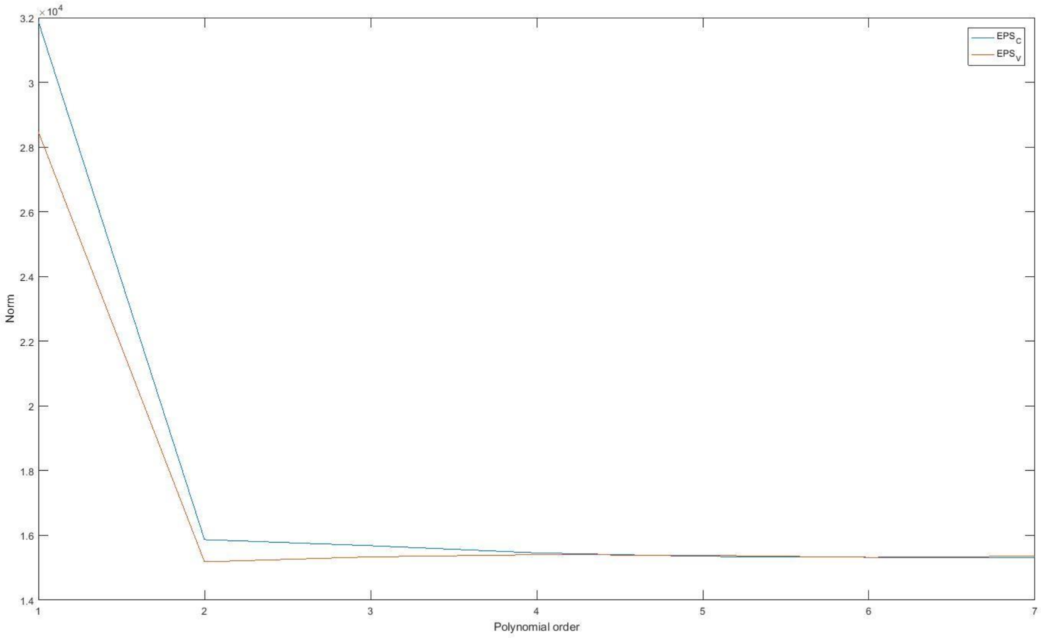


Figure 21: Results of the polynomial order analysis for ballast´s stiffness

N	ε_{cal}	ε_{val}
1	31879,33	28471,44
2	15870,58	15183,02
3	15681,98	15336,82
4	15459,3	15404,05
5	15351,02	15384,43
6	15324,05	15322,46
7	15317,62	15357,96

Table 7: Calibration and validation´s results for ballast´s surrogate model for the ballast stiffness

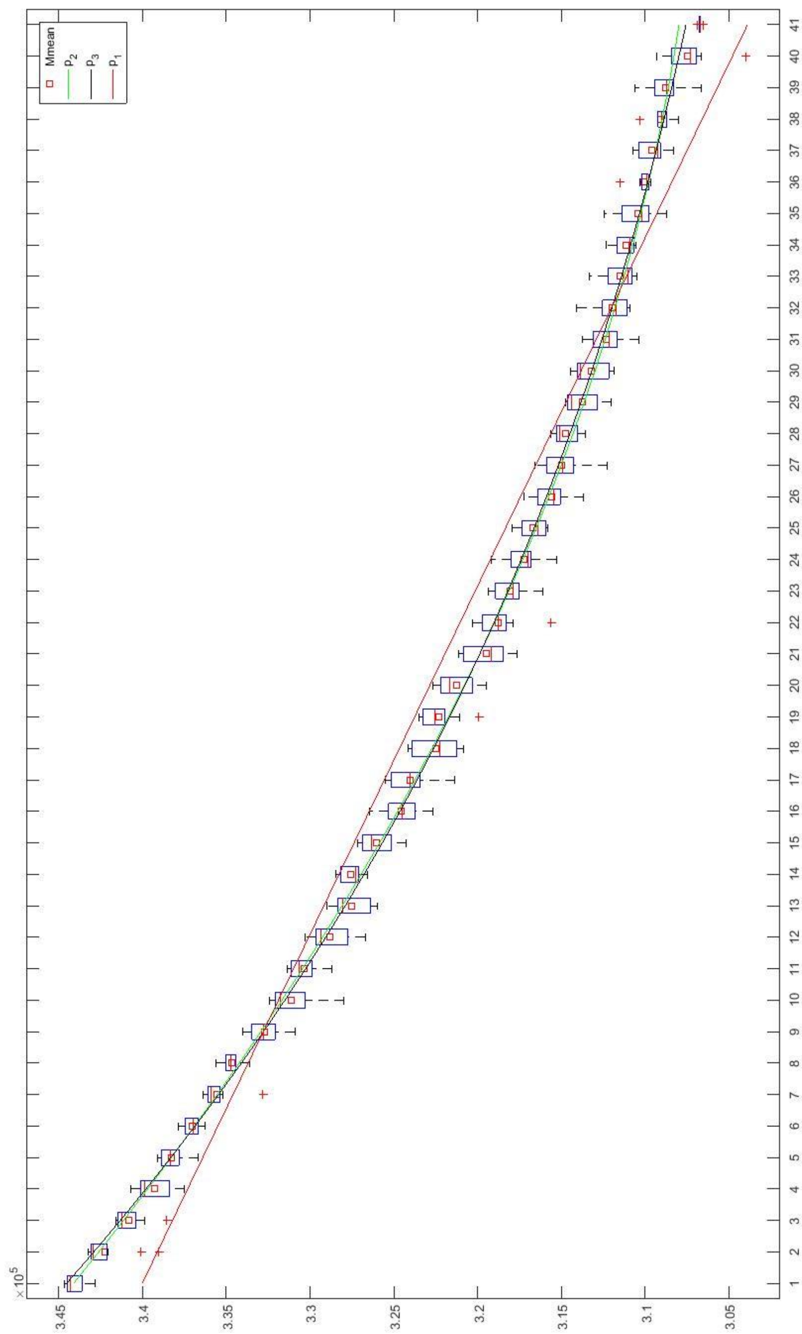
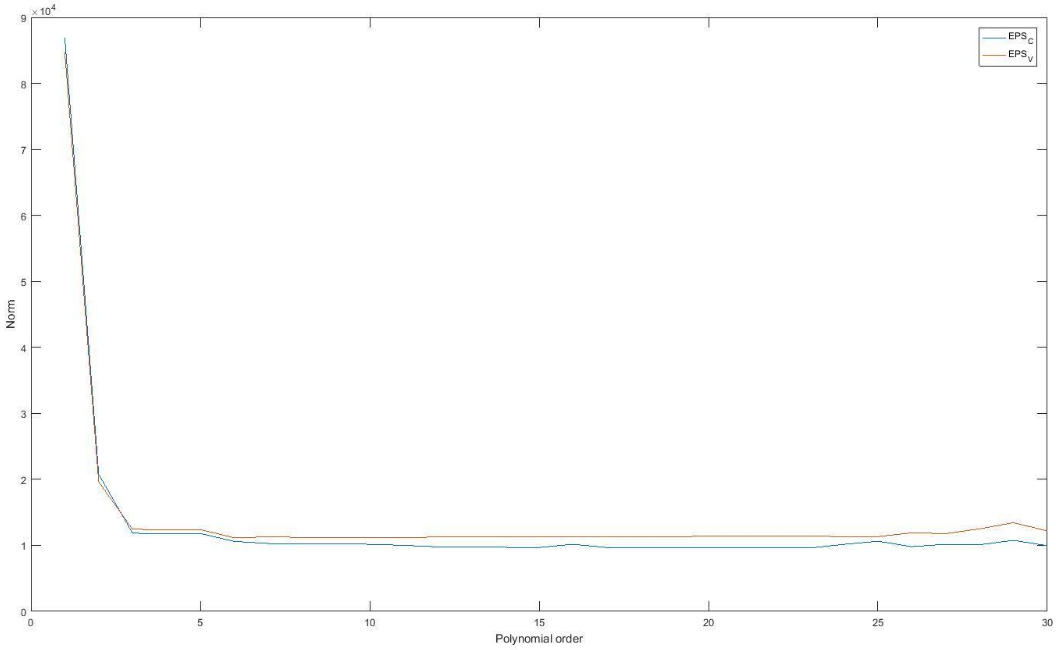


Figure 22: Polynomial models and box-plot of the numerical noise´s samples of the ballast´s stiffness

Surrogate model´s smoothness of the pad´s stiffness

For pad´s stiffness results are shown below. Smoothness´s studies lead to a 3-order polynomial, since the norm has a local minimum.



Figur 23: Results of the polynomial order analysis for pad´s stiffness

N	ε_{cal}	ε_{val}
1	86846,15	84647,83
2	20791,16	19632,45
3	11833,18	12431,73
4	11796,97	12385,01
5	11796,73	12392,5
6	10601,54	11138,38
7	10279,8	11292,21
8	10234,95	11205,05
9	10227,82	11233,08
…	….	…
30	9950,613	12175,14

Table 8: Calibration and validation´s results for pad stiffness´s surrogate model

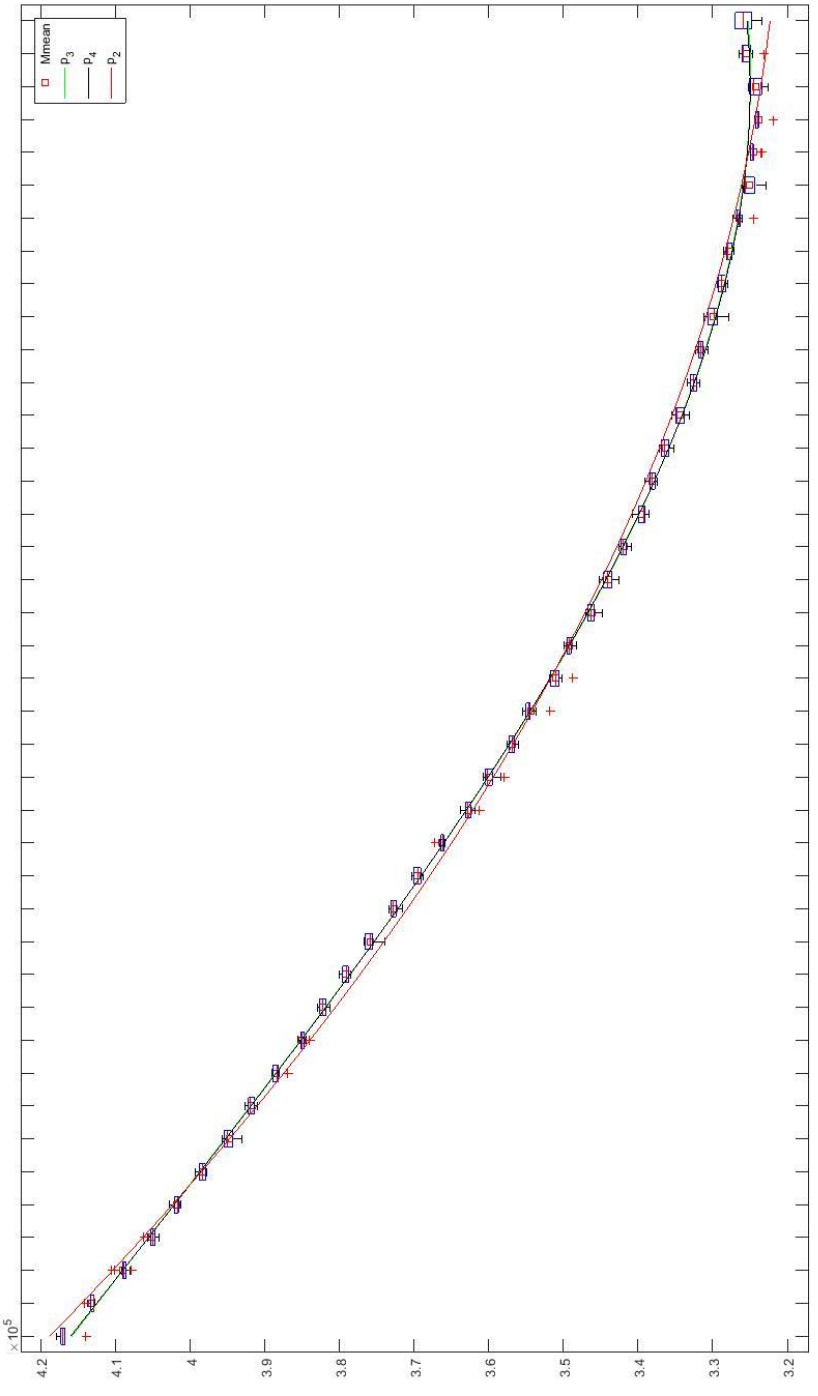


Figure 24: Polynomial models and box-plot of the numerical noise´s samples of the pad´s stiffness

Surrogate model´s smoothness of the speed

For the speed results are shown below. Smoothness´s studies lead to a 10-order polynomial, since the norm has a local minimum.

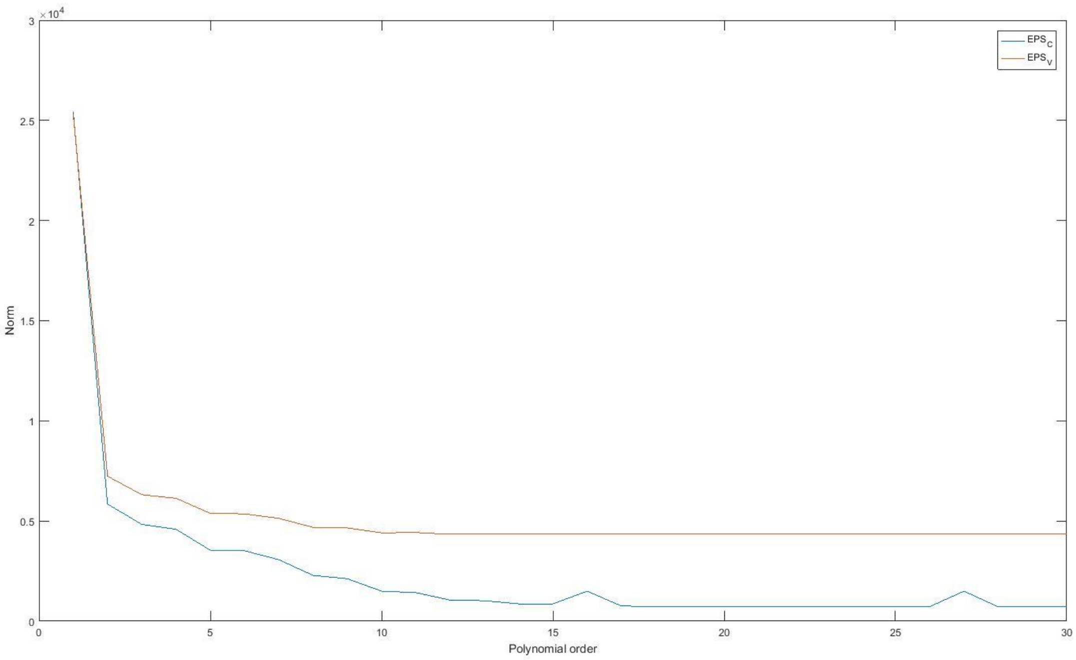


Figure 25: Results of the polynomial order analysis for speed

N	ε_{cal}	ε_{val}
1	25410,44	25291,54
2	5846,486	7237,8
3	4830,594	6313,502
4	4585,998	6133,958
5	3540,441	5381,218
6	3512,99	5356,335
7	3068,862	5132,491
8	2284,59	4681,69
9	2118,935	4655,748
10	1498,424	4408,678
...	...	...
30	716,3793	4358,632

Table 9: calibration and validation´s results for speed´s surrogate model

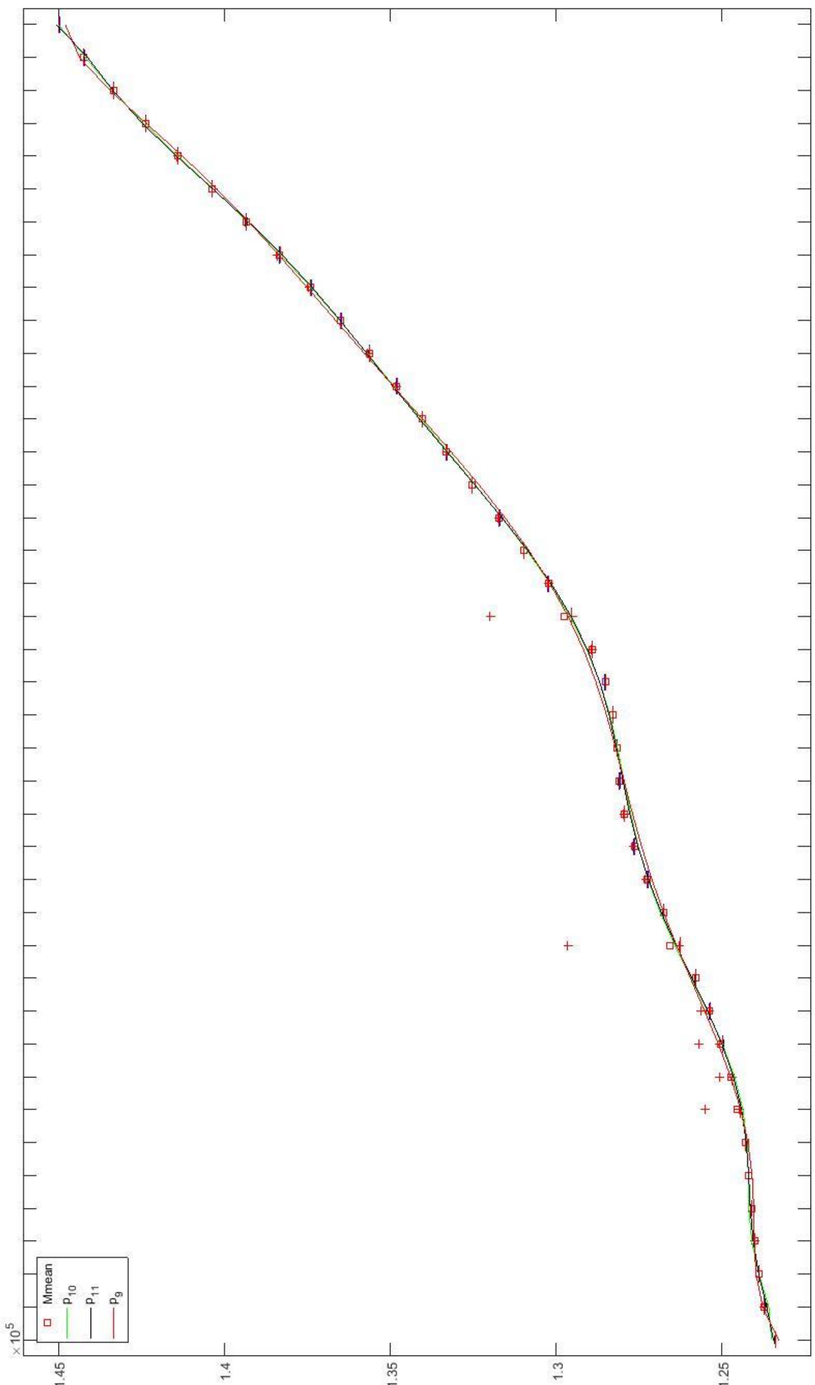


Figure 26: Polynomial models and box-plot of the numerical noise´s samples of the speed

Surrogate model´s smoothness of the wheel-flat length

For the wheelflat´s length results are shown below. Smoothness´s studies lead to a 10 order polynomial, since the norm has a local minimum.

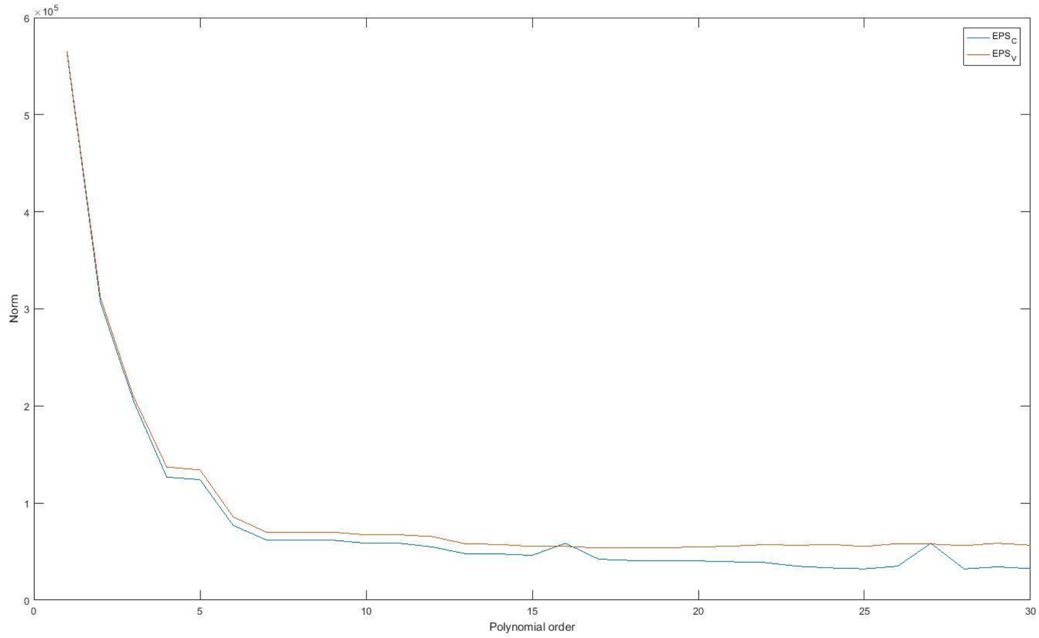
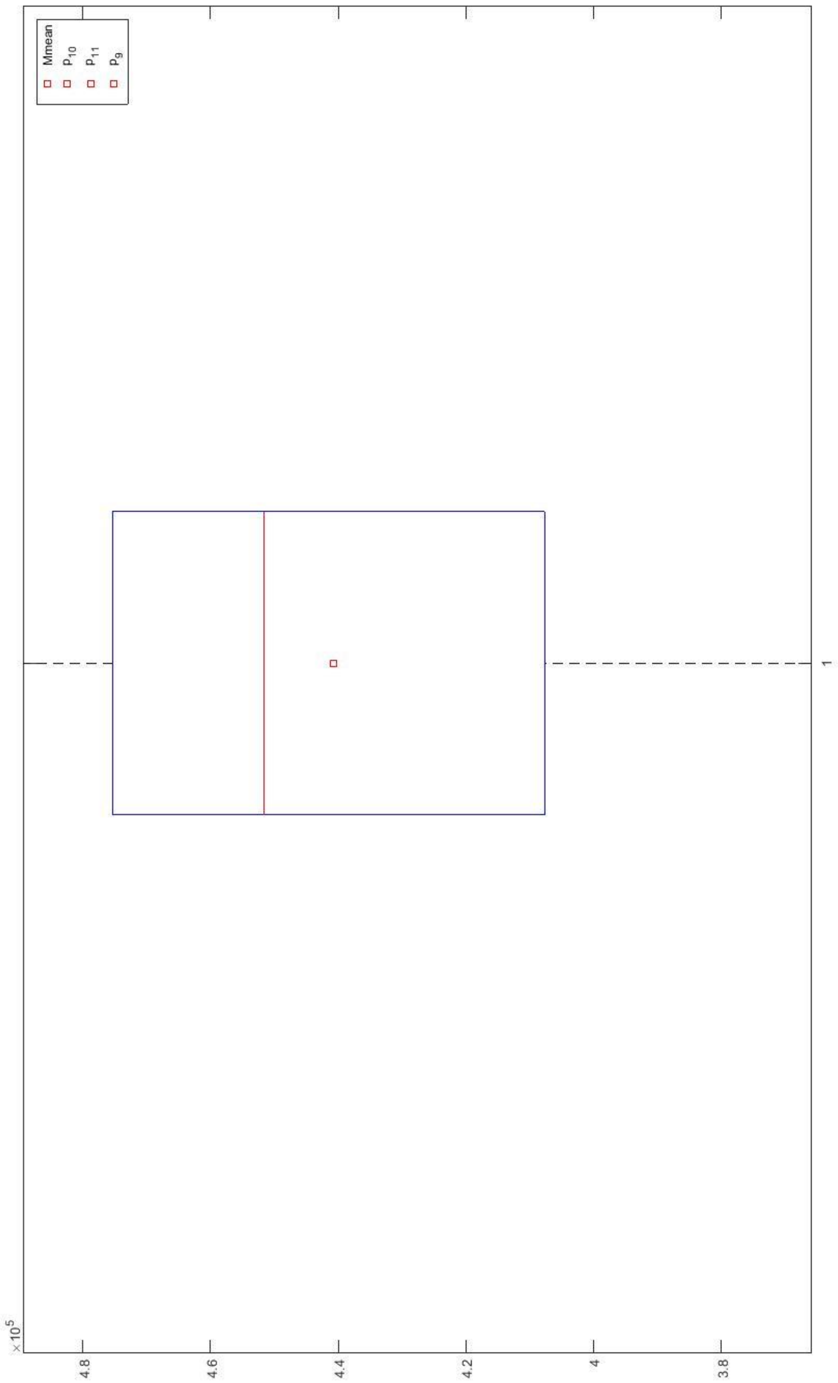


Figure 27: Results of the polynomial order analysis for wheelflat length

N	ε_{cal}	ε_{val}
1	944645,4	929189,8
2	423884,7	428591,1
3	264439,1	291433,8
4	260757,8	290644,9
5	240793,9	267321,3
6	149223,4	179411,2
7	131636,1	160340,3
8	120412,3	153236,4
9	118999,3	152731,1
10	115759,5	147392,5
…	…	…
30	87716,31	113629,9

Table 10: Calibration and validation´s results for wheelflat length ´s surrogate model



Figur 28: Polynomial models and box-plot of the numerical noise´s samples for the wheelflat lenght

In this specific case a truncation of some unreliable data has been made and the output is quite strange. Since with a mapping procedure the cumulative density function is considered the truncation made leads to the mean value. So, the three curves are practically overlapped.

3.3 Multi-variable polynomial model

As mentioned above, an optimization of the response surface is an issue. It is important to take into account that a single surface of infinitive response functions has been analysed, due to the complexity of the optimization process.

The methodology of factorial design is used. In the code adaptMPOLY it is performed. It has been stopped manually due to long time consuming.

By running the code, it is possible to obtain a large number of functions evaluations, more or less 2000. Function evaluation, actually, consists to create samples of experiments at various surface levels.

By using a n-order polynomial function it is possible to obtain a certain smoothness of the surface. Two variables have been selected, with different order in polynomial. The selection of the adequate order has been done before and leads to a 2nd order polynomial for the pad´s stiffness and a 10 for the speed.

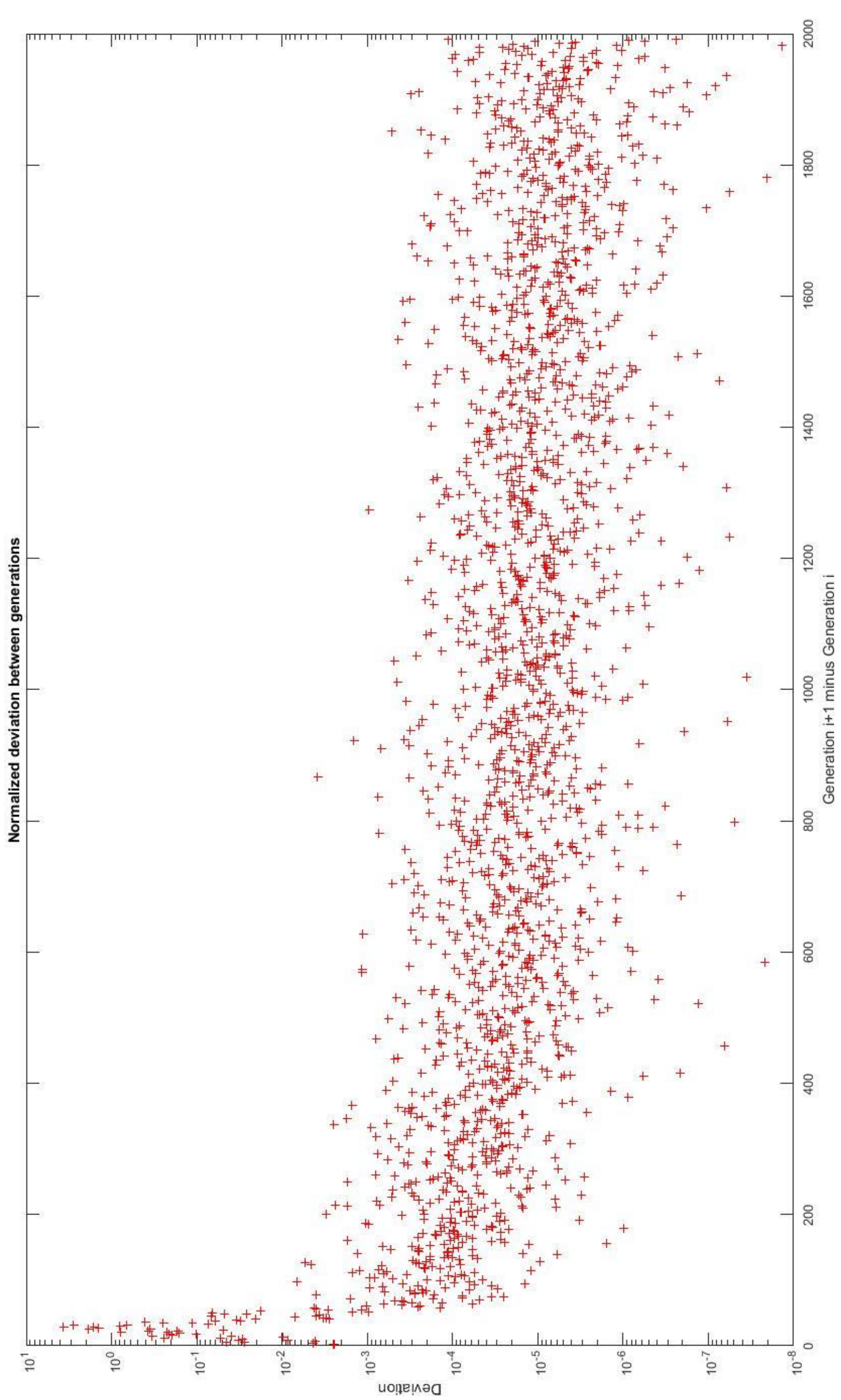
A Nelder mead approach is used to select randomly the points of the surface this could justify an adequate number of function evaluations, with an efficiency´s reduction. The selection of points is only forced in the edges of the visualization´s space, where the exactness of the solution for different variables is obtained. This is due to probability that failure can occur in the edges.

Once the edges are created, in the code a meta-model is used. By adding new evaluation´s samples new smoothed surfaces have been generated, with increasing accuracy. The process is adaptive and with increasing the number of evaluations, error is lesser and lesser. A theoretical limit of the error has been inserted manually, it is of the order of 10^{-10}. Practically with this strong limit the code can run for an infinite period.

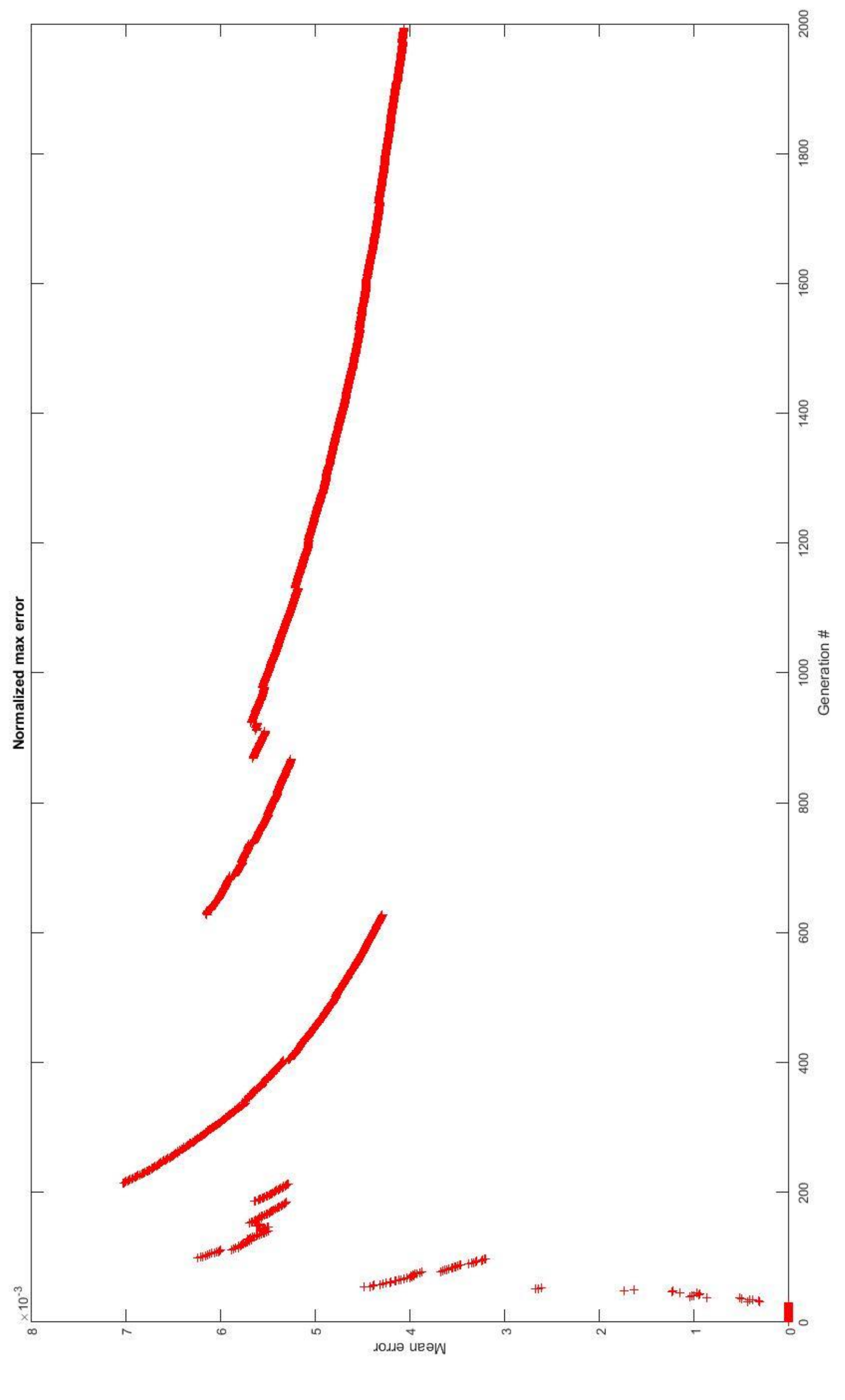
3.3.1 Observations from surrogate model fitting

Since the present study an accuracy´s study of surrogate models is suitable, the analysis of the unavoidable associate error is necessary. In the following figure the error associated to two consecutive generations is shown, and the mean and the max errors between generated samples at time t and surrogate model. It is obtained by minimizing the frobenius norm.

As a result, the error between two different generations decreases with increasing the number of functions of evaluations. In order to correctly interpret the second and third graphs, one could observe a ‘jump’ in the shape of the two errors. This is not related to unreliable data but is given by the random selection of the samples in the surface. The size of the jump then decreases with increasing number of evaluations, this is due to the fact that more points are generated.



Figur 29: Normalized deviation between generations



Figur 30: Normalized max error

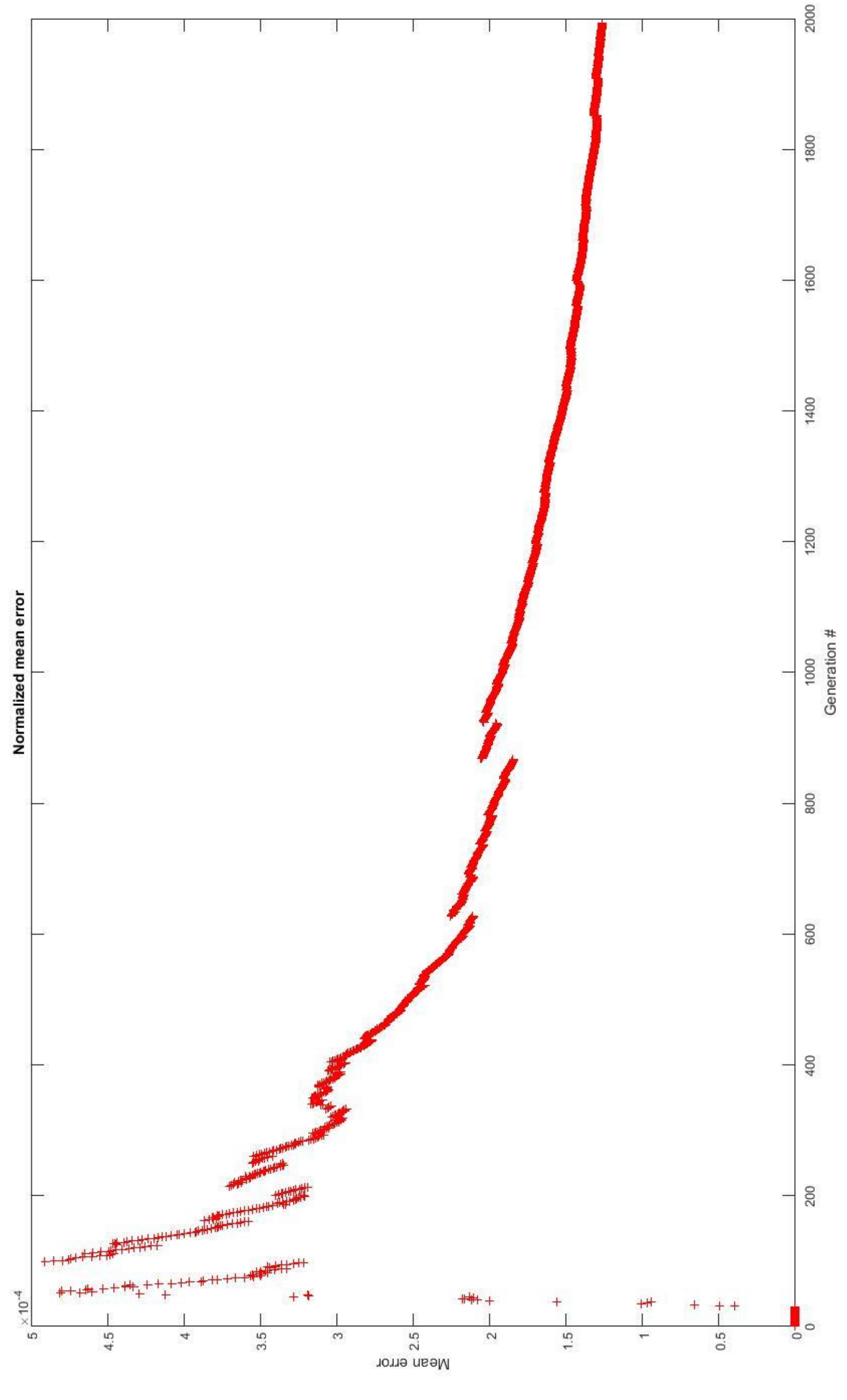


Figure 31: Normalized mean error

Concluding remarks

In the modeling of complex phenomena, the response surfaces or rather the hypersurfaces represent the means by which it is possible to analyze the behavior of a given parameter. The importance of visualizing a performance function is remarkable as the interaction between the multiple dimensions of the problem is complex. In fact, as in the case of the railway field, this complexity is expressed through the interaction between microscopic and macroscopic phenomena. In fact, it is not difficult to come across situations where tolerances in the implementation even if infinitesimal lead to disasters in terms of performance. This is true especially when the complexity of the problem becomes high and where control is therefore more difficult to do. Therefore, structural monitoring and control are huge engineering challenges. The accuracy in predicting the response is therefore a goal especially when, as in the case of railways, safety also invests in human resources. In this thesis work it shown that modeling is required on several levels and the concatenation between these is a further model. Once an accurate model has been used to identify the path of the variation in time of the chosen performance-parameter the next step should be to build a model that has a more intuitive value. In fact, the future works of this project could lead to build another model to identify the 'safe' and the 'unsafe' zones. This leads to study a POF: the probability of failure. The next steps involve FORM and SORM models that are useful to measure the distance in term of safety. This is necessary to make assumptions or to revise those previously made.

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Appendices

A. Variability of track-related physical properties

Steel for structural use

It is known that the crisis can occur due to production defects of the materials that constitute the railway system. For example, if we consider the wheels or the rail, often it can be associated with the different stages of steel production in the furnaces. Technological progress has made it possible to greatly improve the production of structural steel. Production of steel´s specification is a performance-based standard; this implies strong controls. In order to characterize the variables in the multi-parameter design, it is noted that the stiffness of steel for structural use can be considered a deterministic quantity. A detailed study of over 40,000 mill test certificates of rolled wide flange (W), welded wide flange (WWF) and hollow structural (HSS) beam section samples mainly from ASTM A992 steels, representative of those most commonly produced for the US and Canadian markets, was performed in [5] and [16]. These authors presented statistical relationships between the material properties (yield and ultimate strengths, modulus of elasticity) and geometric properties (flange/web thicknesses, web depths, diameter to thickness ratios) of these sections, and offered mean values and coefficients of variations on the most important material parameters. The data set was even large enough to allow these to be reliably related to the known steel chemistry of the different samples.

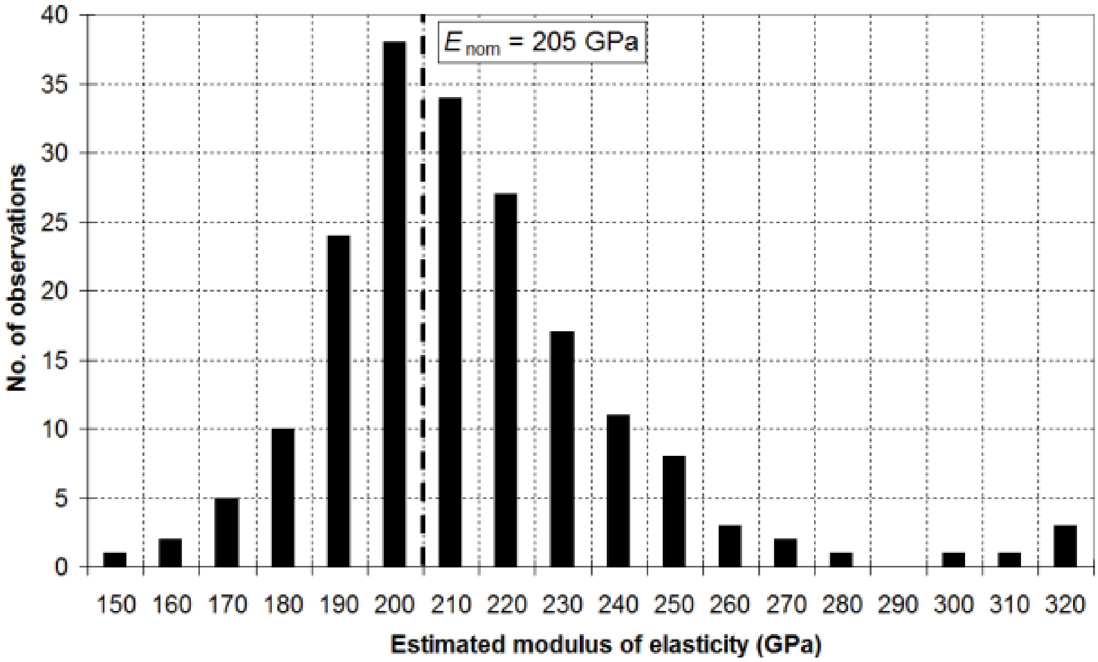


Figure 32: Statistical results from Schmidt and Bartlett´s study

This study justifies the traditional engineering practice, which has always accepted the elastic modulus as material constant. For the purpose of this thesis´s work, the characterization of a certain quantity is related to an element of descriptive statistics: the CV.

	S235JR (obs = 120)				S355J2+N (obs = 31)				S550MC (obs = 23)			
	σ_y	σ_u	h	n	σ_y	σ_u	h	n	σ_y	σ_u	h	n
mean	410.1	465.9	1.08	13.0	405.7	569.7	2.36	6.6	630.8	678.1	0.87	9.5
characteristic	316.2	384.2	0.32	6.5	353.0	538.9	1.06	3.1	576	623	0.40	1.6
min.	278	331	0.04	3.2	350	536	0.97	2.3	575	622	0.39	1.1
max.	578	621	2.44	30.9	602	670	3.09	12.5	705	738	1.61	14.4
nominal	235	360	*n/a*	*n/a*	355	470	*n/a*	*n/a*	550	600	*n/a*	*n/a*
st.dev.	53.1	51.5	0.45	5.54	69.1	29.1	0.53	2.39	33.7	37.3	0.28	3.47
SE	4.9	4.7	0.04	0.51	12.4	5.2	0.10	0.43	7.0	7.8	0.06	0.72
CV	12.96	10.97	40.79	39.77	17.04	5.1	22.62	36.38	5.3	5.5	31.45	36.45
skew	0.27	0.39	0.43	0.61	0.70	0.22	-0.08	0.15	0.54	0.11	0.61	-0.63
kurtosis	1.16	0.79	0.95	0.03	0.60	-0.34	-0.19	-1.11	0.08	-1.34	1.14	0.18

Table 1: Statistical parameters from Schmidt and Bartlett´s study

The study of Schmidt and Bartlett suggests values between 1.9% and 4.5% and Dexter et al. suggesting 2.4% to 3.4%. Material properties with a CV this low can effectively be treated as deterministic, even in probabilistic design.

Reinforced concrete

A preliminary overview is necessary about the elastic modulus of the sleeper´s concrete. Differently from the steel of the rail, reinforced concrete is a composite and concrete is a heterogeneous material affected by a strong time-dependency. About the composition and packaging of concrete, technology has enabled high performance to be achieved. Each element that constitutes the track is subjected to train passages whose effects lead to different results. In the case of concrete, they mainly concern the phenomena of cracking, which lead to a rapid decrease in the concrete´s stiffness. In order to avoid incurring speculations that are not useful in this thesis work, to make a consideration is necessary. Actually, the composition, the different stresses, the diffusion of the fractures would lead to consider the concrete as a highly stochastic variable. However, the scale of the problem plays a fundamental role here. Due to the fact that in this thesis work we are focusing on the design of the railway sleeper, or better, on the optimization of the design parameters, any local or specific effect will not be considered. Referring to the study of authors Sakdirat Kaewunruen and Alex M. Remennikov ` *Progressive failure of prestressed concrete sleepers under multiple high-intensity impact loads* ` impact loading conditions on railway tracks are often caused by wheel or rail abnormalities such as flat wheels, dipped rails, etc. Cracks in railway concrete sleepers have been often observed due to the impact load, even though the possibility of occurrence for this large magnitude load is very low. The current design method for prestressed concrete sleepers does not consider the ultimate behavior under such impact loads. The widespread notion about the reserved strength of a concrete sleeper has raised the concern to develop its new ultimate limit states design concept. The sleeper is then studied in a first phase where the accumulation of deformations is not actually involved yet. This leads us to consider the sleeper concrete as a variable in which the spread of data is linked to the production processes themselves and therefore to the regulations in force.

In particular, the concrete used in this application is a high-performance concrete. The same is subjected to dynamic tests in order to recreate in the laboratory what actually happens in the field.

Therefore, as regards concrete, reference is made to the EN 206-1 standards.

Rail pads

It is known that they have been introduced mainly as damping and noise reduction devices. The choice of the pad is of considerable importance. As mentioned above, the track is a system in which the combination of stiffnesses must be analyzed. Therefore, associating a stiffness to the rail pad is a first issue. It must also be considered that the rail pad influences the overall stiffness as it interacts with two elements characterized by very different materials and, consequently, by very different stiffnesses. The choice of the pad is based on experience and is therefore a compromise where the engineering judgment is in the foreground. For the sake of completeness different material used in pad are cited. Three basic materials constitute rail-pads: natural rubber, EVA and polyurethane. It should also be remembered that these materials are highly dependent on temperature. In order to establish a probabilistic approach, it is reasonable to expect that the stiffness related to a rail pad could have a strong variability. The table below is intended to illustrate the broad differences between different types of pads, and the influence of rate of loading and temperature on stiffness in relation to static stiffness.

Rail pad	Static secant stiffness $k_{40\text{-}80kN}$	Dynamic stiffness at low frequency F_{stat} = 43 kN F_{dyn} = 25 kN at 10 Hz			Dynamic stiffness at high frequency F_{stat} = 20 kN X_{dyn} = 5 µm at 100 Hz		
		0°C	20°C	40°C	0°C	20°C	40°C
A	67	65 (0.20)	55 (0.16)	49 (0.12)	75 (0.19)	56 (0.13)	40 (0.10)
B	71	89 (0.23)	95 (0.20)	82 (0.20)	83 (0.20)	70 (0.14)	49 (0.10)
F	50	90 (0.3)	59 (0.2)	51 (0.15)	140 (0.43)	60 (0.3)	43 (0.19)
G	47	66 (0.25)	55 (0.2)	49 (0.16)	71 (0.28)	53 (0.22)	37 (0.15)
H	226	590 (0.14)	380 (0.16)	190 (0.19)	620 (0.13)	430 (0.13)	240 (0.17)

Table 2: VIBRATEC Silent Track report 81223/3/VIBR/T/A. A Laboratory characterization of rail pad dynamic properties.

The strong variability of the pad's stiffness also depends on how the pad is stressed. More precisely, its dynamic response is influenced by the intensity of the vibrations. Different train speeds will lead to very variable vibrations. The table below shows the results of some tests carried out by Pandrol in Denmark. Different types of pads have been tested. Static and dynamic tests have been carried out at each load level. Each pad type has been tested between the dynamic loads prescribed by EN13481-2.

Pad type	# tested	20 – 70 kN		20 – 95 kN	
		Static	Dynamic	Static	Dynamic
		kN/mm	kN/mm	kN/mm	kN/mm
6530 studded rubber	3	77.3	144.1	96.5	177.8
7850 studded EVA	3	94.1	208.2	103.5	206.4
12672 plain EVA	3	*495.9*	*1473.5*	*548.1*	*1573.8*
12672 plain HDPE *	1	*1023.4*	*1140.5*	*1121.6*	*1309.0*
Zw661a 6mm plain EVA	1	*511.8*	*841.0*	*585.0*	*1037.2*

Table 3: Test results on pads used in Denmark

Omitting aspects that would be redundant in this thesis work, we can state that the direct effects of pad stiffness on track behavior are on:

· Quasi-static load distribution of wheel forces

· Dynamic forces generated at wheel-rail interface

· Wayside airborne rolling noise

· Rail roll and deflection of the fastening system

It is considered useful to report the synthesis of all the effects investigated in the research mentioned above.

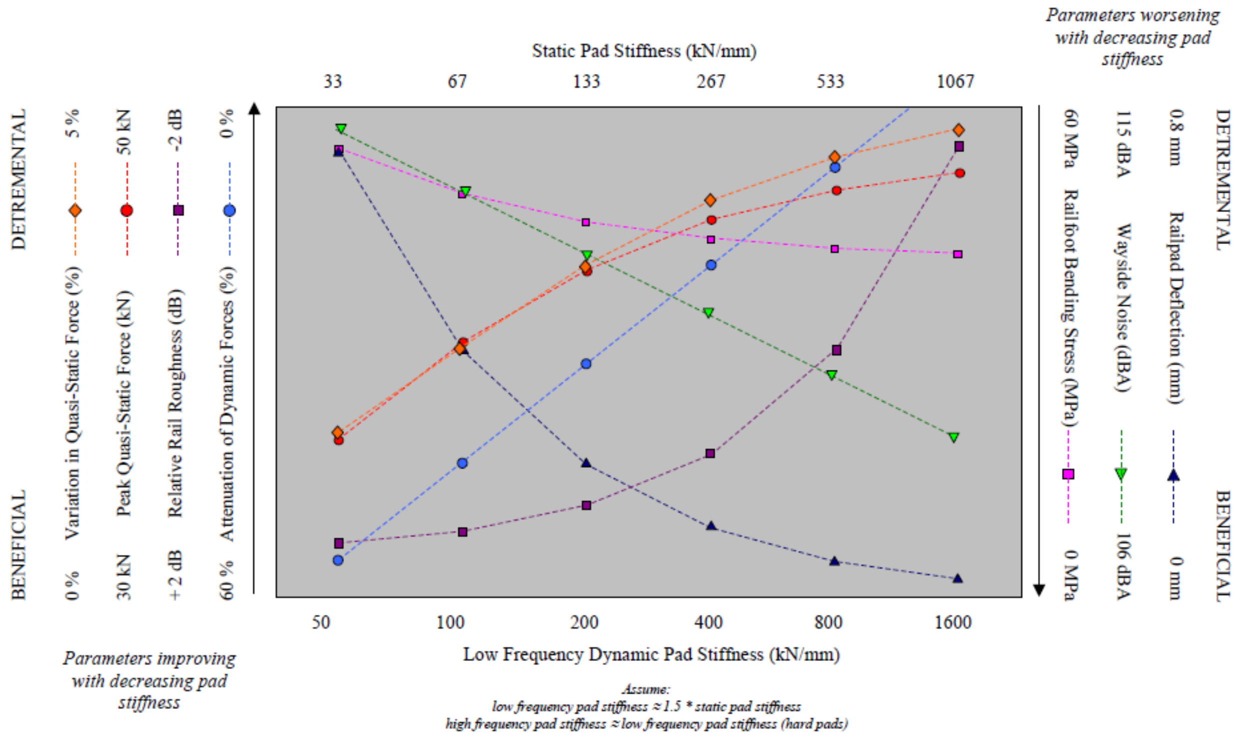


Figure 33: Synthesis of effects of pad stiffnesses

The distribution of published data is reported. For further details refer to the paper 'Reducing the Adverse Effects of Wheel Impacts on Special Trackwork Foundations' (2004) published by the Transportation Technology Center and sponsored by the US Department of Transportation includes a literature survey of pad stiffness values.

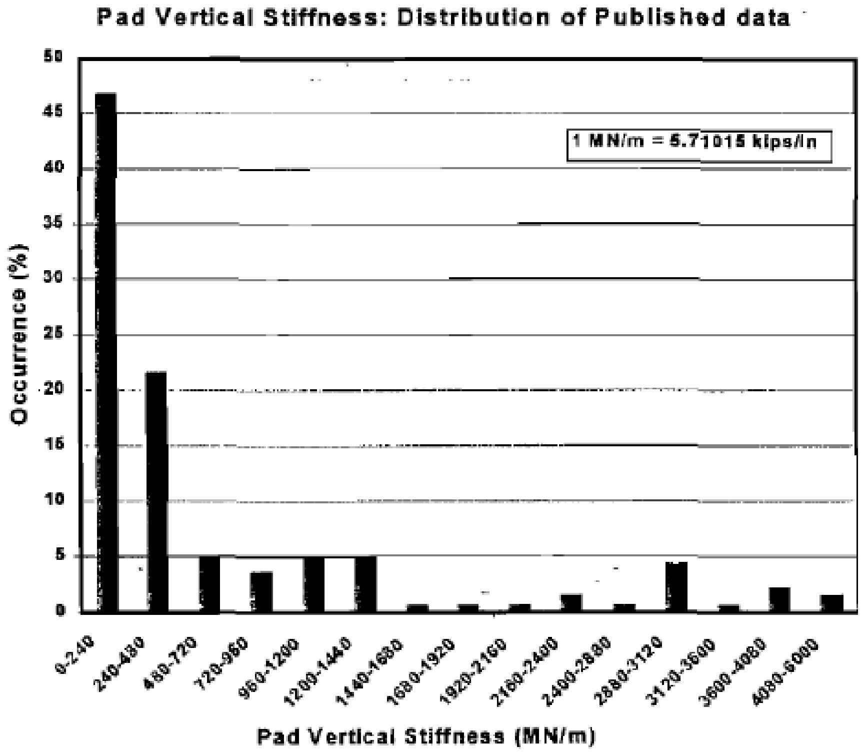


Figure 34: Survey of pad stiffness values

Differently from the elastic modulus of steel, it is possible to observe that the distribution is very different from the Gaussian one. This suggest to consider the rail-pad´s stiffness as a stochastic variable. In this work a certain range of variability of pad stiffness is taken to account by considering multipliers in the input file.

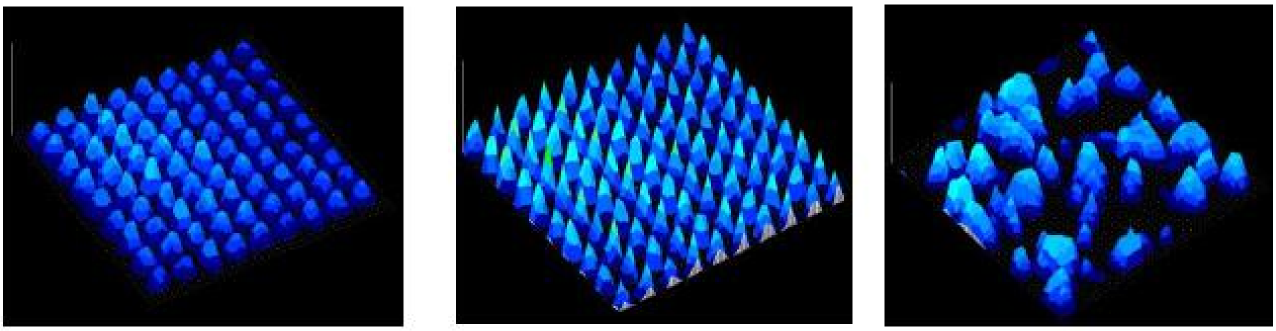
Ballast´s stiffness

The ballast has a fundamental role for the correct behavior of the railway system. The state of maintenance of the ballast is essential to create the necessary friction to avoid derailment. In addition to his structural function it provides a damping effect of the dynamic´s phenomena and of the noise associated with the passage of the train. It constitutes an element of transition between the railway superstructure and the subgrade and it is then characterized by a large variability. Time-dependence is also an important aspect because as the train passes, the mechanical properties of the ballast change and the interaction with the superstructure behaves differently in time, consequently. Its characterization is complex because of its discontinuity: it´s a granular material, roughly coarse and where important mass forces are generated. This shows how, differently from the rail steel, the study and maintenance´s planning of the ballast are very difficult to operate. Different methodologies and studies were made to analyze the behavior under load of the ballast. In this thesis work a dissertation on the models and different methodologies will not be reported, but rather a brief introduction on the complexity of the ballast itself was made, to underline its complexity in the structural response of the railway system.

Contact points between the sleeper and the ballast´s particles therefore constitute very important elements to perform a tentative characterization of the stiffness of the ballast support. In optimization´s problems then, a continuous and control monitoring would be necessary. The settlements at the ballast-sleeper interface are coupled to the stresses in the sleeper. Therefore, the measurement of the pressure between ballast and sleeper plays a fundamental role. Behind the simulations there is a technique to measure the pressure at ballast-sleeper´s interface. This is based on a thin-film technique. Different typologies exist: Marshek et al. (1986) used a pressure sensitive film to measure the static pressure, a polyvinylidene fluoride

(PVDF) film has been used by Marsili (2000). Anderson used the Matrix Based Tactile Surface Sensor (MBTSS) technology.

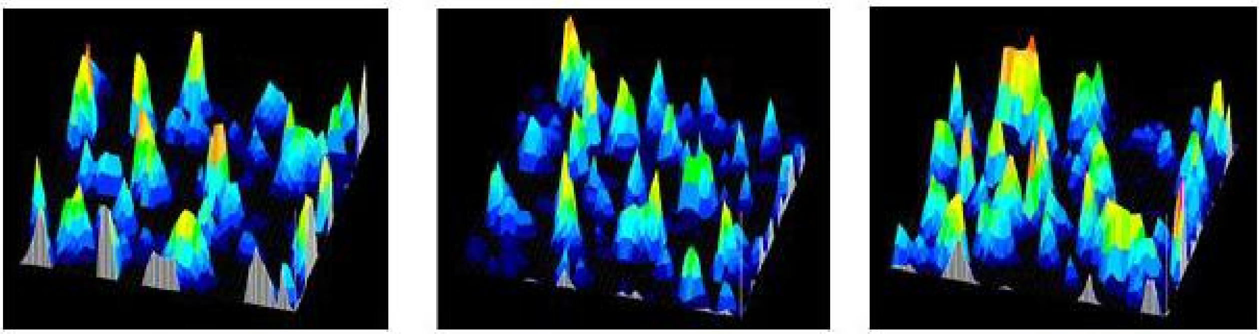
The following figures show an extract of a calibration process using the MBTSS technology devised by Teskan. Through this instrument an aluminum waffle is inserted and the calibration is carried out. In the following figures it is pointed out that only when the pressure is measured at the tie-ballast interface, the calibration leads to a strong variability despite the test performance being sufficiently accurate. This underlines how the ballast can be considered as a free stochastic variable par excellence and a complex modeling is necessary. Strong approximation and simplification could lead in greater probability of error in the characterization.



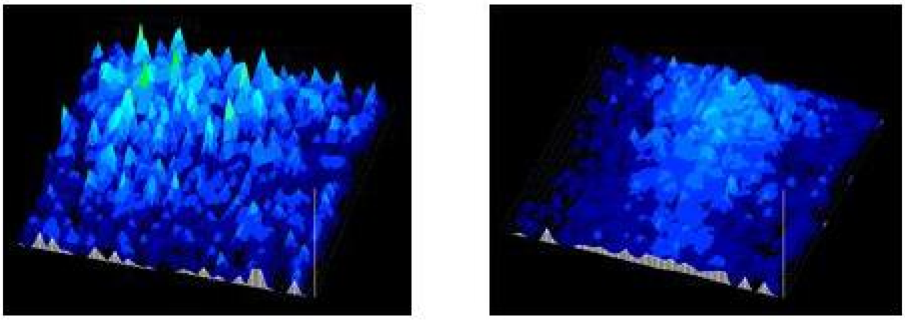
(a) (b) (c)

Figure 35: Comparing the pressure distribution shapes for the same sensor reacting against (a) inch waffle plate, (b) 0,25 inch waffle plate and (c) surface of fouled ballast at the same raw sum.

A distinction of five types of ballast was made in order to access the complexity of the ballast´s characterization.



(b) New Ballast (b) Moderate Ballast (c) Fouled Ballast

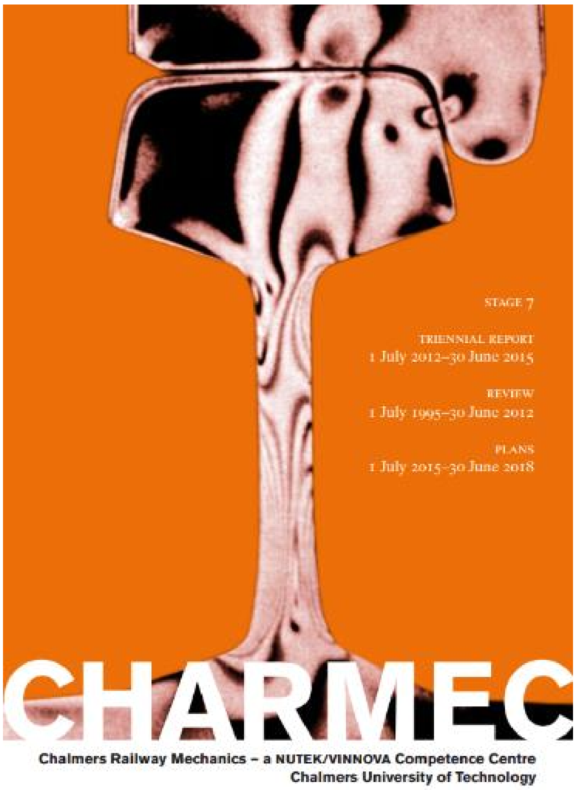


(d) Pea Gravel (e) Sand

Figure 36: A typical pressure distribution for each of the five ballast materials at 10 kips of applied load

B. The railway mechanics center CHARMEC

This work is part of the on-going research activities in the national railway center of excellence CHARMEC.



The Competence Centre CHAlmers Railway MEChanics, abbreviated CHARMEC, was established in July 1995 at Chalmers University of Technology in Gothenburg, Sweden.

It had its origin in a small-scale railway mechanics research programme which was set up in 1987, at the Department of Solid Mechanics (since 2005 part of the Department of Applied Mechanics) in collaboration with the company Sura Traction (now Lucchini Sweden).

A key factor to the success of CHARMEC has been the long-term commitment of the Swedish Transport Administration Trafikverket (previously Banverket) and the industrial partners. Four of the current twelve partners during Stage 7 (including Lucchini) have been involved since 1995, and another four have been involved for twelve years or more. Two members served on the CHARMEC Board from 1995, one of them up to June 2014 and one until the end of Stage 7. Another key factor is the core group of committed CHARMEC researchers at Chalmers University of Technology who have served the Centre for a long time, and are still actively involved. Some of them have worked for CHARMEC since the start in 1995, or even from the start of the railway-related activities in 1987. The Swedish Governmental Agency for Innovation Systems (vinnova) organized a third international evaluation of CHARMEC at the end of the Centre's Stage 3. Conclusions from the evaluators were: CHARMEC has established itself as an internationally recognized multidisciplinary Centre of Excellence in railway mechanics. No such evaluation has taken place since 2003. However, in 2011 vinnova initiated an investigation into the impact CHARMEC has had on the companies that participated in different research centres. CHARMEC and several of our partners have contributed to this study.

Semi-annual reports are also included in the general organization.

Partners and financial report

In the following table principal partners and contributions are reported. Contribution could be cash or in-kind. Cash is referred to the real contribution. In-kind is referred to the reported work and then to the amount of hours. Trafikverket's contribution is the most relevant one.

Party	Cash		In-kind		Total	
	Budget	Paid	Budget	Performed	Budget	Paid/Performed
Chalmers	15 180	15 180	9 800	9 800	24 980	24 980
Abetong	1 440	1 440	660	334	2 100	1 774
Bombardier	2 400	2 240	1 500	1 506	3 900	3 906
Faiveley	1 155	1 155	600	515	1 755	1 670
Green Cargo	660	660	330	0	990	660
Interfleet	180	180	150	131	330	311
Lucchini	1 485	1 485	900	1 134	2 385	2 619
SJ	660	660	–	–	660	660
SL	1 455	1 455	330	51	1 785	1 506
SweMaint	150	150	150	0	300	150
Trafikverket	17 704	17 704	1 500	690	19 204	18 394
voestalpine	2 145	2 145	2 460	2 445	4 605	4 590
ÅF	300	300	150	119	450	419
UIC	645	645	–	–	645	645
VINNOVA	1 609	1 609	–	–	1 609	1 609
EU	2 990	2 990	–	–	2 990	2 990
From Stage 6	3 792	3 792	–	–	3 792	3 792
Total	53 950	53 950	18 530	16 725	72 480	70 675

Table 1 Cash and in-kind contribution (Ksek) per party

Vision and goals

CHARMEC is a strong player among world-leading research centers in railway mechanics and contributes significantly towards achieving lower production, maintenance, operating and environmental costs and to overall improvement in the safety and quality of railway transportation. The University, Trafikverket and the Industry collaborate in realizing this vision. CHARMEC successfully combines the identification, formulation and solution of industrially relevant problems with high academic standards and internationally viable research. CHARMEC disseminates its research results and contributes to industrial development and growth in Sweden and abroad. Charmec maintains an up-to-date body of knowledge and preparedness which can be put to use at short notice in the event of unexpected damage or an accident during railway operations in Sweden or abroad. The scientific level and practical usefulness of CHARMEC's academic and industrial achievements are such that continued long-term support to charmec is profitable for the Government, the University and the Industry. CHARMEC's specific goals include the national training and examination of Licentiates and PhDs and the international presentation and publication of research results. Fundamental and applied research projects are integrated. CHARMEC's industrial partners are supported in the implementation of the solutions that are reached and the use of the tools that are developed. CHARMEC attracts able and motivated PhD students and senior researchers. The Licentiates and PhDs who graduate from charmec make attractive employees in the railway industry and associated r&d organizations. CHARMEC's research focuses on the interaction of various mechanical components. Analytical, numerical and experimental tools are developed and applied. New and innovative materials, designs and controls are explored. The life-cycle optimization of parts and systems for track structure and running gear is intended to slow down the degradation of ballast and embankments, increase the life of sleepers and pads, improve track alignment stability, reduce rail and wheel wear, reduce the tendency towards rolling contact fatigue of rails and wheels, reduce the levels of vibration and noise in trains, tracks and their surroundings, and improve systems for the monitoring and operation of brakes, bearings, wheels, etc.

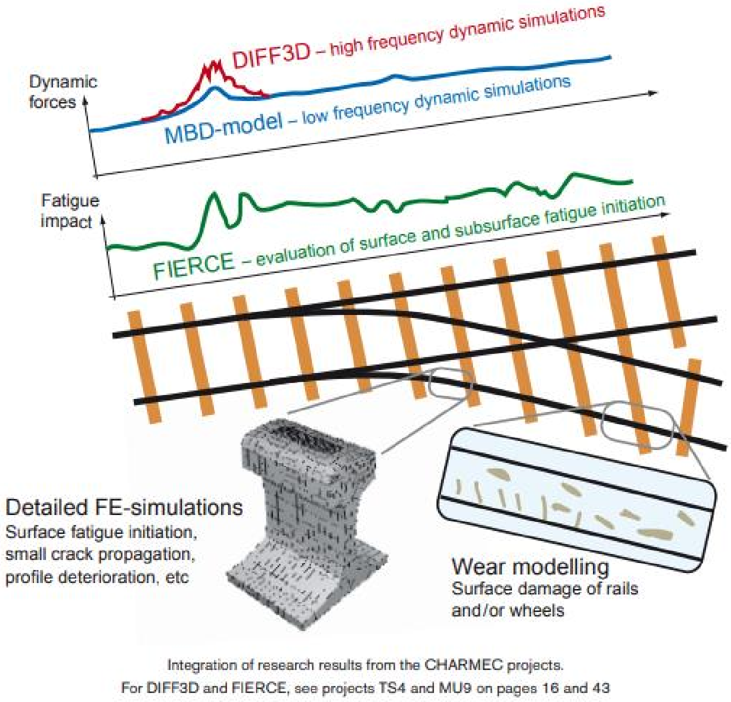


Figure 37: a scheme of modeling/optimization

Programme areas charmec stage

The Competence Centre CHARMEC should work within six overall programme areas as set out below.

Programme area 1 **Interaction of train and track**

Programme area 2 **Vibrations and noise**

Programme area 3 **Materials and maintenance**

Programme area 4 **Systems for monitoring and operation**

Programme area 5 **Parallel EU projects**

Programme area 6 **Parallel special projects**

Interaction of train and track

A rolling train is a mobile dynamic system that interacts, via the wheel-rail interface, with the stationary track structure, which in turn is a dynamic system. This interaction is a key area within all railway mechanics research. The mechanisms behind vibrations, noise and wear depend on the interplay of the rolling train and the track structure. The activities of this programme area are directed towards being able better to understand, model and predict the dynamic interaction for different types and conditions of trains, tracks and operations. Analytical, numerical and experimental methods are used.

Vibrations and noise

A considerable reduction in vibrations and noise from railway traffic seems to be of crucial importance to the future acceptance of this type of transportation. The generation and spread of vibrations in trains, tracks and environment and the emission of noise are phenomena that are difficult to approach, both theoretically and experimentally. The activities in this programme area are directed towards achieving a better understanding of the underlying mechanisms. Advanced analytical and numerical tools and well-planned laboratory and field experiments and measurements are required. The goal is to establish a basis for effective modifications and counter-measures against vibrations and noise in trains and tracks and in their surroundings.

Materials and maintenance

Suitable and improved materials for axles, wheels, rails, pads, sleepers, ballast and embankments are a prerequisite PROGRAMME AREAS CHARMEC STAGE 7 for good mechanical performance, reduced wear, lower maintenance costs and an increased technical/economic life of the components mentioned. The activities in this programme area are directed towards analysing existing materials and developing new materials. A knowledge base should be created for the rational maintenance of train and track components. Co-operation between several different competences are required for this research.

Systems for monitoring and operation

Brakes, bearings, axles, wheels and bogies are important mechanical components of a train with regard to its operational economy and safety. There seems to be considerable potential for improvement for both passenger and freight trains. New components and new ways of improving and supplementing existing functions should be studied. A systems approach is emphasized and the work is performed in a cross-disciplinary environment, drawing on several different academic and industrial competences, including solid mechanics, machine elements, signal analysis, control theory, and computer engineering and mechatronics.

Parallel EU projects

CHARMEC has represented Chalmers University of Technology as a partner in several eu (European Union) projects in railway mechanics since the Fourth Framework Programme in 1996 up to Horizon

2020. All our eu projects are closely related to charmec's ongoing research programme areas 1, 2, 3 and 4, and charmec contributes to the funding of these eu projects.

Parallel special projects

At a meeting on 10 September 2002, the charmec Board decided to gather and list a number of our bilateral agreements and separate research and development projects in railway mechanics under the above heading. This programme area includes both short-term and long-term projects, several of which have been established for the industrial implementation of CHARMEC's research results.

Hannover-Hamburg disaster

A disaster occurred on 3 June 1998, near the village of Eschede in the Celle district of Lower Saxony, Germany, when a high-speed train derailed and crashed into a road bridge. CHARMEC group gave a technical opinion of what happened. Train operator was Deutsche Bahn.

C. Nomenclature

$Ballast$: it is a coarse and granular material. His function is fundamental to provide friction to the sleeper. A dissipation of loads is also achieved. It also transfers the pressure from the rail to the subgrade.

$Rails$: they are the element that guide the train. Their particular shape allows to correctly run the train´s wheels in different alignment´s configurations. By the structural point of view, they provide bearing capacity to the train´s wheels.

$Rail-pads$: rail pads provide a dumping effect for high frequency vibrations and constitute a protection for the sleeper. They are placed between the rail and sleepers. Different materials are involved in rail-pads such as rubber, Eva and polyurethane.

$Sleepers$: their function is to transfer loads from the rail to the ballast. Their interaction with ballast is fundamental because a friction is necessary to avoid buckling. Wood sleeper are neglected in modern railways and concrete sleepers are used nowadays. Normally the spacing is fixed between $0.5 - 0.65$ m.

OFP Non-destructive testing

$UT\ \ Ultrasonic\ \ testing.$ The method is used for internal detection cracks / defects.

$PT\ \ Penetrant\ \ Test\ \ (Penetration\ \ Test)$

The method is used to detect surface defects (cracks and other defects that occur in the surface). The method fits all materials which is not porous.

MT Magnetic Particle Testing The method is used to detect surface defects (cracks and other defects that occur in the surface). The method can only be used on magnetic materials.

VT Visual (ocular) inspection

ET Inductive test (vortex test) The method is used for detection of cracks and other defects that occur in the surface.

Methods for conducting non-destructive testing are manual testing trial made by hand with handheld instruments or with a manual trolley.

Figure 1: An example of OFP

The Swedish Transport Administration applies definitions of broken, broken and damaged rails according to UIC 712 R / TDOK 2014: 0598 (formerly BVH 524,100), Catalog of rail faults.

Broken rail (rail crash) A rail that has either been displaced in two or more parts or a rail from which the cuttings were loosened so that a gap of more than 50 mm in the carriageway occurred and deeper than

10 mm.

Cracked rail A rail with one or more visible or invisible cracks that do not have any particular pattern or position in the rail profile and whose growth can quickly lead to rail crash.

Damaged rail A rail that is neither cracked nor broken but has other defects, usually in the road surface.