THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Towards Model-Based Condition Monitoring of Railway Switches and Crossings

MARKO D.G. MILOSEVIC

Department of Mechanics and Maritime Sciences

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2021

Towards Model-Based Condition Monitoring of Railway Switches and Crossings
MARKO D.G. MILOSEVIC

Thesis for the degree of Licentiate of Engineering – Department of Mechanics and Maritime Sciences
2021:16
Department of Mechanics and Maritime Sciences
Division of Dynamics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Cover: Paper B results for measured and simulated sleeper displacements

Chalmers Reproservice
Gothenburg, Sweden 2021

Towards Model-Based Condition Monitoring of Railway Switches and Crossings
MARKO D.G. MILOSEVIC
Department of Mechanics and Maritime Sciences
Chalmers University of Technology

Abstract

Railway switches and crossings (S&C, turnouts) connect different track sections and create a railway network by allowing for trains to change between tracks. This functionality comes at a cost as the load-inducing rail discontinuities in the switch and crossing panels cause much higher degradation rates for S&C compared to regular plain line track. The high degradation rates create a potential business case for condition monitoring systems that can allow for improved maintenance decisions compared to what can be achieved from periodic inspection intervals using measurement vehicles or visual inspection by engineers in track.

To this end, this thesis addresses the development of tailored processing tools for the analysis of measured data from accelerometers mounted adjacent to the crossing transition in crossing panels. With the presented tools, a condition monitoring framework is established. The analysis procedures showed robustness in processing large datasets. The framework includes the extraction of different crossing panel condition indicators for which the interpretation is supported by multi-body simulations (MBS) of dynamic train–track interaction. Additionally, a demonstrator is presented for MBS model calibration to the measured track responses.

A particularly important signal processing tool is the development of a novel sleeper displacement reconstruction method based on frequency-domain integration. Using the reconstructed displacements, the track response is separated into quasi-static and dynamic domains based on deformation wavelength regions. This separation is shown to be a promising strategy for independent observations of the ballast condition and the crossing rail geometry condition from a single measurement source.

In addition to sleeper acceleration measurements, field measurements have been performed in which crossing rail geometries were scanned. The scanned geometries have been implemented into a MBS software with a structural representation of the crossing panel, where analyses have been performed to relate the concurrently measured accelerations and crossing rail geometries. To address the variation in operational conditions in the MBS environment, a sample of measured wheel profiles was accounted for in the analysis. This MBS study showed that there is a strong correlation between the crossing rail geometry condition, wheel–rail contact force, and crossing condition indicators computed from the dynamic track responses. Contrasting measured and simulated track responses from the six investigated crossing panels showed a good agreement. This observation supports the validity of the simulation-based condition assessment of crossing rail geometry.

Based on the work in this thesis, a foundation is set for developing methods for automatic calibration of S&C MBS models and subsequent damage evolution modelling based on operational online condition monitoring data. This development aims to address S&C service life in a digital environment and presents a key component for building a Digital Twin prototype for S&C condition monitoring.

Keywords: Switches & crossings, S&C, condition monitoring, multi-body simulations, MBS, model calibration, dynamic vehicle–track interaction, wheel–rail contact forces, sleeper void, crossing rail geometry, condition indicators, embedded sleeper accelerometer, displacement reconstruction.

To the Poet, the Mathematician, and the Logos

Preface

The work presented in this thesis was accomplished at the Division of Dynamics at the Department of Mechanics and Maritime Sciences, Chalmers University of Technology, between February 2019 and May 2021. It was performed as part of the activities within the National Centre of Excellence in Railway Mechanics CHARMEC (CHAlmers Railway MEChanics, www.charmec.chalmers.se) within the project TS21 – "Model-based condition monitoring of railway switches and crossings". Parts of the research have been funded within the European Union's Horizon 2020 research and innovation program in the project In2Track2 under grant agreement No. 826255. The project has been supported by CHARMEC's industrial partners. In particular, the support from Trafikverket and voestalpine Railway Systems GmbH is gratefully acknowledged.

Acknowledgements

To my mentors, nice and smart people: Björn!, Jens, Håkan, Arne.

To M2 Dynamics professors, colleagues, and friends: Anders, Roger, Peter F., Angela, Viktor, Thomas, Peter M. Magnus, Elena, Tore, Jim, Rostyslav, Mladen, Knut, Emil, Michele, Ata, Johan, Kourosh, Saptarshi, Anna-Lena, Carina, Pernilla, Jonas, Boban.

To my family, that I am far away from for years now, I hope to see you more: Gordana, Dusan, Strahinja, Nikola, Luka, Jelena.

To my friends, from Novi Sad: Predrag, Ljubinko, Nemanja, Ivan, Filip, Nikola S., Bojan, Stefan, Nikola K., Ognjen; from Delft: Uros, Marko, Georgios, Marios, Ioannis, Filippos, Arthuro, Vlad, Andrei; from Gothenburg: Vladimir, Svetozar, Aleksandar, Nebojsa, Branko, Jovan, Milos, Dalibor, Nikodim, Milan, Aleksej, Stefan, Goran, Velimir, Vesna, Punisa, Milica, Mladen, Bora, Mico, Mile, Nikolaj, Mijo, Ivana, Snezana, Stojica, Milena, o.Igor, Jefimija, Konstantin, Zorka, o.Dusan, Aleksa, Mihajlo, Slavica, o.Nektarije, o.Nemanja, o.Dragan.

Thank you all, it is my honour to have this opportunity, in something important for me, to mention your names!

Thesis

This thesis consists of an extended summary and the following appended papers:

Paper A Marko D.G. Milosevic, Björn A. Pålsson, Arne Nissen, Jens C.O. Nielsen, Håkan Johansson, Reconstruction of sleeper displacements from measured accelerations for model-based condition monitoring of railway crossing panels, To be submitted for international publication, 26 pp, 2021.

Paper B Marko D.G. Milosevic, Björn A. Pålsson, Arne Nissen, Jens C.O. Nielsen, Håkan Johansson, Condition monitoring of railway crossing geometry via measured and simulated track responses, To be submitted for international publication, 27 pp, 2021.

The appended papers were prepared in collaboration with the co-authors. The author of this thesis was responsible for the major progress of the work including taking part in planning the papers, developing the theory and the numerical implementations, running the simulations, and writing the papers.

Contents

Part I

Extended Summary

1 Introduction

1.1 Background and motivation

In a railway network, the components that connect two tracks and switch trains from one track to another are called switches & crossings (S&C, turnouts). This switching operation comes at a cost since S&C feature load-inducing rail discontinuities that cause much larger degradation rates compared to regular plain line track. Consequently, the high degradation rates of S&C are the reason why railway infrastructure managers spend from tens to hundreds of millions of Euros annually on their maintenance. In Sweden, the annual maintenance cost for around 12 000 S&C is estimated to 400 – 450 MSEK (~ 40 – 45 MEUR), which corresponds to around 12% of the total maintenance cost [1]. In the United Kingdom, the corresponding cost in 2012 for the around 20 000 S&C was 189 MGBP (~ 212 MEUR), with an additional cost for renewals of 220 MGBP (~ 246 MEUR) [2]. For example, Germany has 69 983 (2014) S&C [2], France 25 600, and Switzerland 15 062 [3]. Additionally, sustainable development-wise, railway transportation is found to be the most energy-efficient form of transportation holding the lowest environmental impact as shown in several studies [4, 5]. This is an important motivation for rail operations. Also, the reliability and resilience of railway transportation are strongly connected to the monitoring and maintenance of its numerous components.

With S&C being an integral component of the railway transportation and with them having a high maintenance cost, a potential business case is open for condition monitoring systems that can improve maintenance decisions compared to those achieved from periodic inspection intervals using measurement vehicles or visual inspection performed by engineers in track. This thesis addresses method developments towards such a system and it is built upon previous work within Chalmers Railway Mechanics Centre of Excellence (CHARMEC) [6-8].

1.2 Aim of research

The objective of this research is to develop a model-based numerical procedure that can identify and predict the structural condition of switches and crossings (S&C) via embedded sensors. The goal is that the system should be accurate enough such that maintenance decisions can be taken based on output from this routine. The target system can be described as a Digital Twin representation of the physical system where simulation models, condition monitoring data, and maintenance history are combined to predict and identify the maintenance needs for S&C.

To this end the following developments have been completed and are presented in this thesis:

- A method for robust signal processing of online condition monitoring data including reconstruction of displacements from measured accelerations and qualitative crossing condition indicators (Paper A)
- A method to observe the crossing geometry condition from operational condition monitoring data including model calibration demonstrator (Paper B)

The following future developments are foreseen:

- An automatic method for calibration of S&C multi-body simulation (MBS) model based on operational online condition monitoring data
- A method for damage evolution prediction for S&C based on calibrated MBS models and long term operational condition monitoring data
- Demonstration of a full Digital Twin prototype for S&C that integrates the previous developments

1.3 Scope and limitations

This research project is multidisciplinary and covers the fields of data acquisition, signal processing, structural mechanics, multi-body dynamics, geotechnics, material science, data analytics, and infrastructure management. Each particular field requires assumptions and simplifications to find an optimal level of accuracy with obtaining a feasible computational effort for developing and using a Digital Twin solution for S&C. Some of the obstacles are the difficulties to perform field experiments for data acquisition, the changing environment (temperature, freezing, humidity) in railway operations that can in the long term affect condition monitoring equipment, unknown track design parameters, uncertainties in soil behaviour and operational variability in train types and axle load. In conclusion, with accounting (and predicting) the above-mentioned obstacles and difficulties, the purpose of this project is set to create a prototype of a Digital Twin solution for condition monitoring of S&C that can be demonstrated and evaluated.

Digital Twins for condition monitoring of mechanical systems are typically physics-based (white-box) or machine learning-based (black-box) [9]. This dichotomy is illustrated with the Digital Twin landscape presented in Figure 1. For the physics-based, the Digital Twin has deep domain knowledge defined by Newtonian mechanics. For condition monitoring applications one of the main goals is to make service life predictions. This can be achieved with models that simulate operational conditions and damage evolution. The limitations of this white-box approach are model uncertainties, overall model capabilities, and potential high computational costs. On the other hand, machine learning-based Digital Twins are governed by data science. Here the data model does not have physical domain knowledge. The advantage of this method is robustness in the sense that the analysis algorithm gets input and with no user interaction produces output. Also, the model can improve over time if it is being continuously trained with new data. But, the training data sets must be obtained and the model cannot operate reliably outside the training domain, which typically does not cover changes of operational conditions and more importantly the outlier events. Thus, the machine learning approach cannot predict failure cases for which it is not trained.

To this end, this research is operating within the physics-based Digital Twin domain. Considering the presented landscape, it is foreseen that the two solutions will be joined in future work such that the limitation of one method can be compensated with the capabilities of the other. For example, simulating operational conditions on damaged S&C (outlier events) and training the machine learning algorithms with this synthetic data.

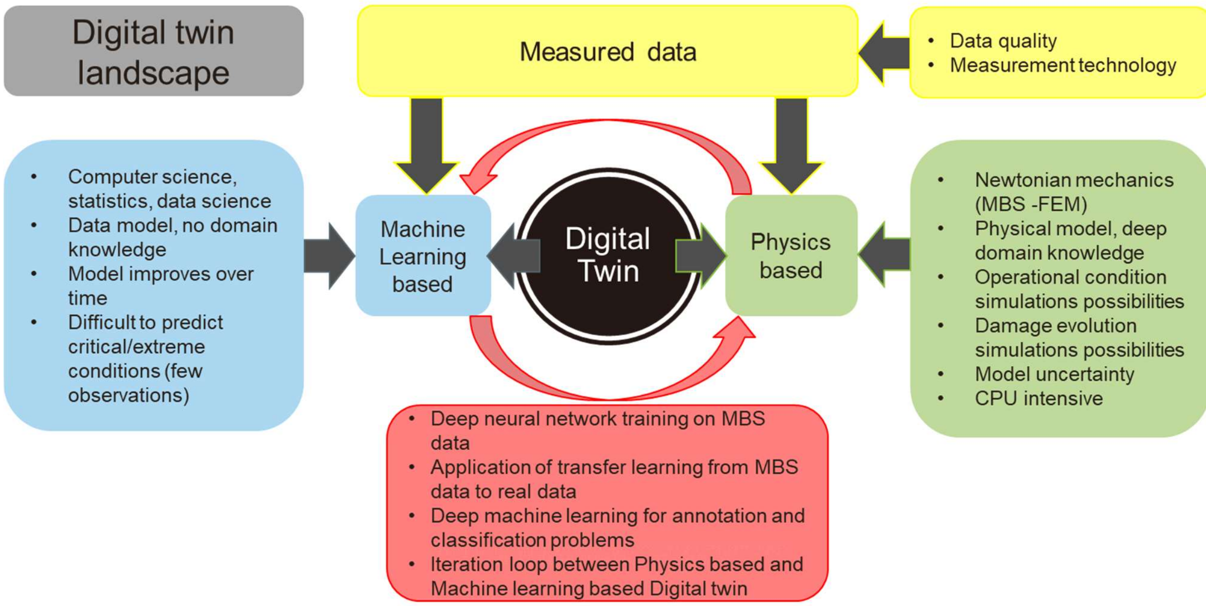


Figure 1 Digital twin landscape for condition monitoring of S&C system.

2 Switches and Crossings overview

2.1 Components

The layout of a standard S&C with a fixed crossing is presented in Figure 2. The main S&C components are the switch panel, closure panel, and crossing panel. In the switch panel, there are flexible switch rails that are actuated with the switching machines to shift position and thereby guide trains into the through or diverging routes. In the crossing panel, the arrangement of rails includes a crossing nose and two wing rails that allow for wheels to travel across the two intersecting routes. Further, there are check rails that impose a lateral constraint on passing wheelsets to prevent excessive lateral movement and derailment during the crossing transition. Traffic in the facing direction (move) goes from the switch panel towards the crossing panel, while traffic in the trailing move goes in the opposite direction.

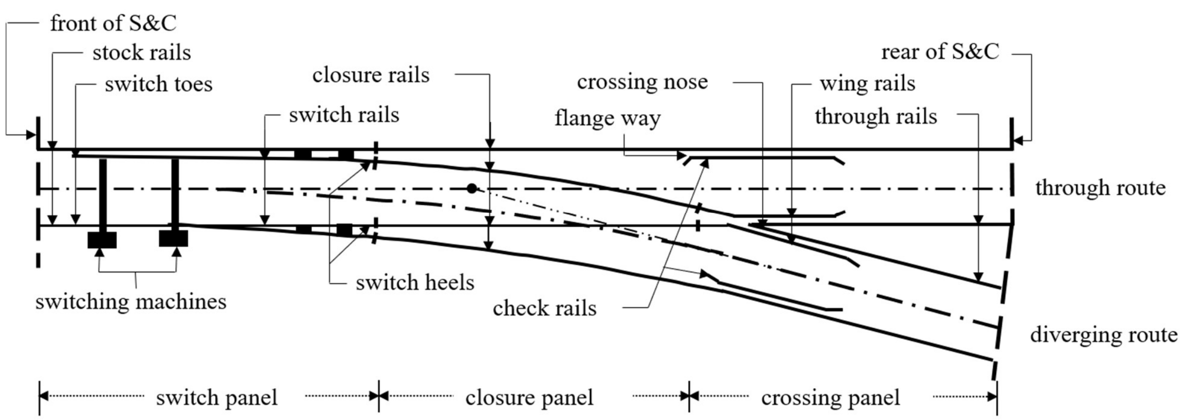


Figure 2. Layout, components, and nomenclature for a standard right-hand side S&C with a fixed crossing [10].

S&C can be installed on ballasted or slab track. This research is focused on the ballasted track. The components of the ballasted track are grouped into superstructure and substructure [11], see Figure 3. The superstructure consists of rails connected with a fastening system to the sleepers. The substructure consists of the ballast, sub-ballast, and subgrade. Ballast is an aggregate formed with crushed stones that forms the top layer of the substructure directly beneath sleepers and supports the track superstructure. It provides track resilience and absorbs energy from the dynamic wheel–rail contact forces that are transferred through the sleepers. This solution provides efficient drainage and easy adjustment of track geometry during maintenance. Beneath the ballast lies the sub-ballast, which is a layer that prevents the mixing of ballast and subgrade. The subgrade is a platform consisting of placed soil and natural ground that creates a foundation for ballast and superstructure. See [7] for further details on S&C design.

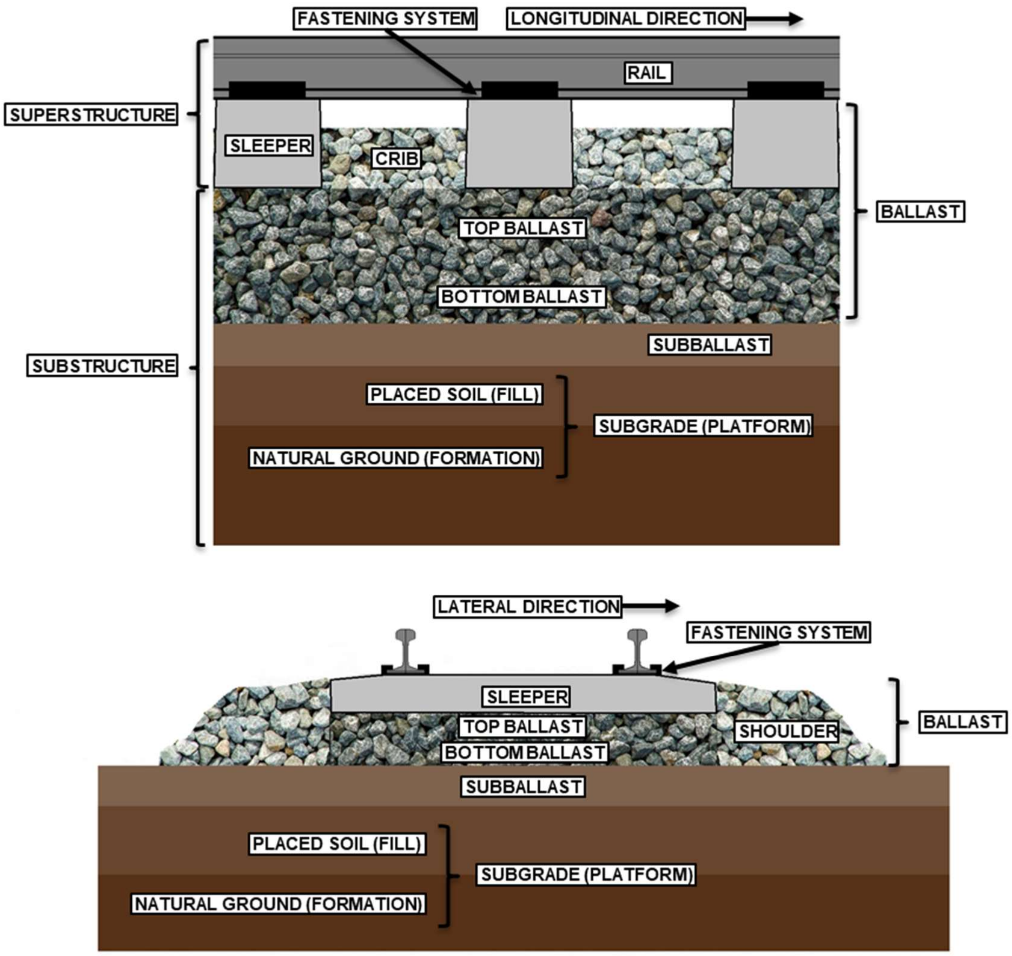


Figure 3 Longitudinal-vertical (top) and transversal (bottom) cross-sections of ballasted track. The nomenclature is based on [11].

2.2 Crossing panel kinematics

This thesis is focused on the crossing panel of an S&C. Additional details on this part are given in the following. Nomenclature for the main crossing panel components and illustration of the variation in contact conditions for passing wheels are presented in Figure 4. The illustration concerns a vehicle passing through the crossing panel in the facing direction in the through (straight) route as indicated by the arrow at the bottom of the figure. Trains coming from the opposite direction travel in the trailing move. The branching track to the right is the diverging route. Regular wheel–rail contact conditions experienced by wheels on each rail side before the transition are illustrated with cross-section details C and E. As the vehicle moves further towards the crossing, for the wheel on the right, the transition from wing rail to crossing nose (detail D) will be associated with an impact load on the crossing nose. This is due to the reversal in vertical wheel displacement trajectory from a slightly downwards motion while rolling on the wing rail to a slightly upwards motion on the crossing nose. If the wheel is hollow worn (concave tread), the given transition occurs later (detail B) and it usually causes much higher dynamic impacts than a regular transition. The main contact for the wheel on the left side is regular contact with the rail, but the back of the wheel might come into contact with the check rail (detail A). The check rail is an important guiding feature to ensure that the wheelset cannot move too far to the right and make improper interference contact between the right wheel and the tip of the crossing nose.

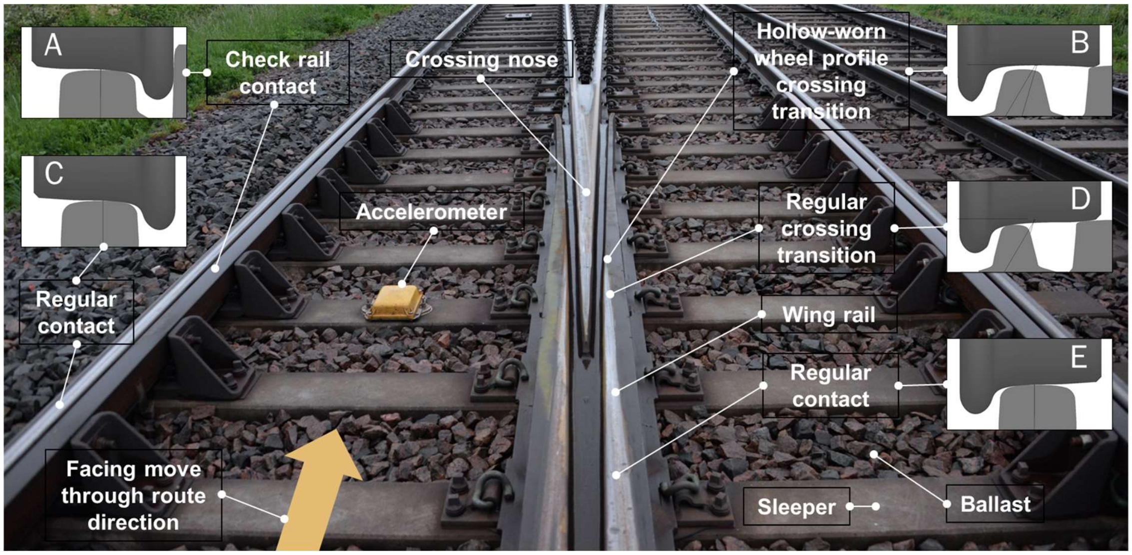


Figure 4 Illustration of a wheelset transition through the crossing panel with the nomenclature for the main components and illustration of wheel–rail contact conditions.

2.3 Vertical vehicle–track interaction in crossing panels

Figure 5 presents a cross-sectional view of a two-layer track structure model of the crossing transition. Starting from the top is the crossing rail. The rail is coupled to sleepers via bushing elements that represent the resilience in the rail to sleeper connections. The sleepers in turn are coupled to rigid ground via bushing elements that represent the ballast and foundation stiffness. The figure also illustrates the location for the accelerometer shown in Figure 4. This accelerometer is permanently embedded in the track, and research in this thesis is using data acquired with this type of sensor.

When a wheel rolls over the crossing as in Figure 4 it excites the track in a broad frequency range. On the low end of the spectrum is the deformation stemming from the static wheel load. Further up in the frequency spectrum is the vertical impact load stemming from the designed discontinuity of the crossing. Based on analytical modelling, this force impulse is expected to consist of two main components [12]. The first is the P1 force (500 – 1000 Hz), which is due to the wheel and rail oscillating out of phase with a frequency related to the contact stiffness. The second is the P2 force, which is related to the wheel and track oscillating together on the foundation stiffness (50 – 100Hz). Naturally, the dynamic response of the real structure can be expected to be broader with a wider range of frequencies excited. However, these analytically derived force components give an indication of the frequency regions of interest for typical system properties and are expected to qualitatively represent fundamental forces and frequencies that are present in the real system. In addition to the loads discussed above, there are rail surface irregularities at short wavelengths causing excitations at even higher frequencies. These dynamic loads cause damage to the crossing and the crossing panel structure. Over time each damage increment can accumulate to failures or deterioration so that large maintenance is needed.

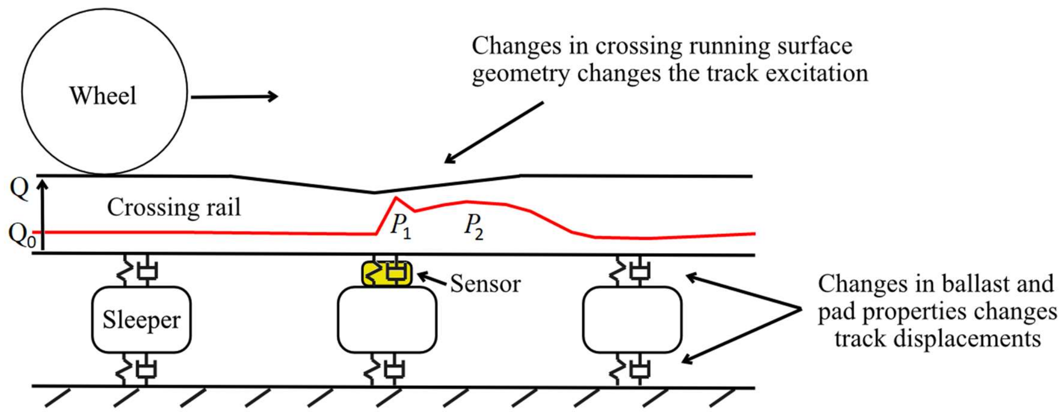


Figure 5 Schematic cross-sectional view in the longitudinal-vertical plane of a wheel rolling over the crossing transition, and illustration of P1 and P2 force.

2.4 Damage modes and maintenance

From a global perspective, the condition of the track in the crossing panel is governed by track geometry and support conditions. An important contributor to track geometry is track settlement [7]. These are permanent displacements that cause irregularities in track geometry when they are not uniformly distributed. The geometric irregularities can cause higher wheel–rail contact forces that cause higher degradation rates. In addition, voids can form between sleeper and ballast resulting in higher dynamic rail and sleeper displacements, see Figure 6. The possible maintenance actions for addressing track geometrical irregularities due to track settlement and sleeper voids are tamping and stone blowing [13].

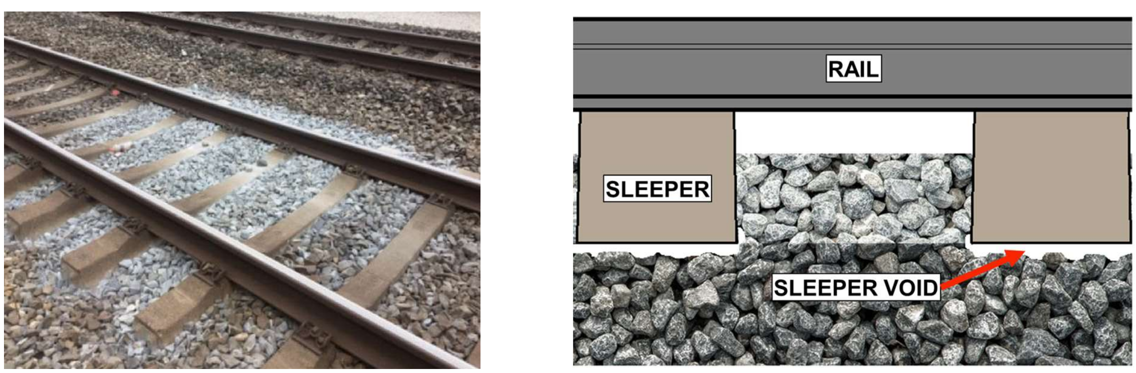


Figure 6 (a) White spots of ballast breakdown due to voided sleeper [14], the picture is courtesy of Prof. Mykola Sysyn. (b) 2D longitudinal cross-section illustration of sleepers with a void.

On a local level, the condition of the crossing panel is endangered by crossing rail plastic deformation, wear, and rolling contact fatigue, see Figure 7. These damage modes directly influence crossing transition kinematic and the resulting dynamic wheel–rail contact forces. Maintenance for such damage modes is grinding/milling, welding repairs, or complete rail replacement. A particular cause of high damage is high wheel–rail contact forces at the crossing panel transition due to poor wheel tread conditions, see Figure 8. For a review on common material degradation mechanisms in S&C see [15].

(a) (b) (c)

Figure 7 Crossing nose degradation states, (a) plastic deformation, (b) wear, (c) rolling contact fatigue. Pictures are courtesy of voestalpine Railway Systems GmbH.

(a) (b) (c)

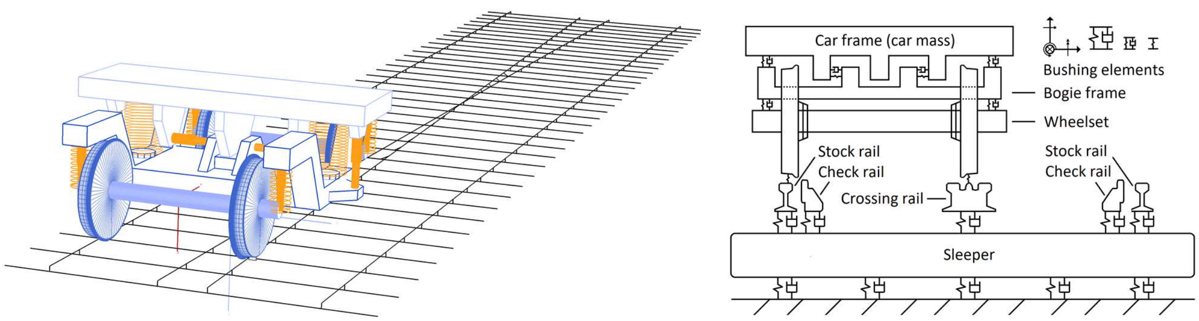
Figure 8 Wheel tread degradation states, (a) hollow worn wheel, (b) severe rolling contact fatigue, (c) long wheel flat. Pictures are courtesy of Prof. Anders Ekberg (a) and Michele Maglio (b,c).

2.5 Multi-body simulations model

The dynamic interaction between vehicle and crossing panel is in this research evaluated by multi-body simulations (MBS) approach. The analyses are performed with the commercial software Simpack (v.2019). The track model is a finite element model with all rails and sleepers modelled by Timoshenko beam elements. Each sleeper is supported by a discretized system of independent bushings in the vertical direction that represents the stiffness and viscous damping of the ballast and subgrade (Winkler bed). Each connection between sleeper and rail is modelled by a single bushing element representing the rail fastening. The degrees-of-freedom for the nodes of the rails and sleepers are partially constrained to reduce model complexity. The sleeper nodes can deform vertically, while the rail nodes can deform vertically and laterally including their corresponding rotations. The model is generated with an S&C model generation script [16] and implemented in Simpack using its non-linear flextrack functionality.

In the presented investigations simulations are performed for reduced track length. It was found that a track model of 21.6 metres in length (37 sleepers) is sufficient for simulating the 12 meters (±6 m) of single train bogie passage over the crossing transition (in facing and trailing moves). The vehicle is modelled as a single bogie according to the passenger vehicle model from the Manchester benchmarks study [17], but with adjusted mass properties.

The crossing rail geometry in the simulations is represented by 2D profiles discretized from the 3D scans of the crossing rail, see Figure 12, or from a nominal generic crossing from the S&C benchmark study [18] that here is used as a reference case. An equivalent Hertz contact is used for the normal wheel–rail contact, while FASTSIM [19] is used to model the tangential contact. The 3D and 2D view of the vehicle–track model is shown in Figure 9.



(a) **(b)**

Figure 9 (a) MBS model of vehicle–track system, and (b) 2D representation of vehicle–track system during a passage through the crossing panel.

2.6 S&C related research

This subsection presents a literature survey addressing three different areas covered in S&C-related research; experimental analysis, instrumentation (sensors), and numerical analysis. On the experimental side, [20] uses ultrasonic guided waves for active structural health monitoring of railway turnouts. The authors claim that the method can detect growing defects in real-time, but not existing defects. In [21], the authors used image processing and machine learning to assess magnetic particle images for the prediction of rolling contact fatigue in crossings. In work [22] two experimental tools are used to measure the dynamic response of a railway crossing. It is found that the magnitude of wheel–rail transition impact forces on the crossing can vary considerably from one train wheel to another in operation. A so-called "fatigue area" criteria is set for damage assessment on the crossing nose. In practice, track measurement cars [23] are often used for monitoring of track irregularities, but they can experience difficulties to measure irregularities in S&C due to the varying rail profiles. For research purposes, instrumented wheelsets [24] are used to measure wheel–rail contact forces.

For the aspect of addressing the long-term condition monitoring, two-dimensional (2D) cross-sections of a crossing rail were recorded at 19 positions over 30 months in intervals of three to six months [25]. By applying a statistical method of filter-based prognostics using track irregularities as input, a prognostics tool for railway track degradation was proposed and demonstrated for four S&C [26].

On the instrumentation side, an overview of the implementation of geophones, accelerometers, and 3D-scanners for S&C monitoring was presented in [27]. Accelerometers and remote video monitoring were used in [22] to resolve crossing rail displacements. In paper [28] micromechanical system (MEMS) accelerometers are studied in the context of S&C maintenance.

Concerning numerical work, the data from [25] was used for damage modelling concerning plastic deformation and wear of the crossing rail in [1]. The CHARMEC competence centre at Chalmers carried out three PhD projects in recent years on the optimization of S&C [6], wheel-rail impact loads, and track settlements in railway crossings [7], and long-term damage evolution in railway crossings [8]. In works such as [29], we can find the use of an explicit finite element method for the analysis of dynamic wheel-crossing interaction. The particular value of those papers lies in the creation of domain knowledge for understanding S&C behaviour.

As a general view on S&C and its maintenance, valuable work is produced in the PhD thesis [3]. Also, a comprehensive study on railway S&C monitoring is presented in the PhD thesis [2], there conclusion is stated that the rate of change of S&C geometry is the key contributor to the development of S&C condition monitoring knowledge. Overall this literature survey addressed the scope of S&C related research questions found in the literature. Further in section 4.1 additional literature survey is presented that contrasts different condition monitoring approaches and presents the S&C condition monitoring framework developed and used in this thesis.

3 Data used in this thesis

The field measurement data used in this research includes 3D scans of crossing rail geometry and acceleration measurements obtained with a permanently embedded sleeper sensor (shown in Figure 4).

3.1 Crossing rail geometry scans

Crossing rail geometry scans have been performed for six crossing panels at three locations on the southern mainline in Sweden. Details for the given crossing panels are presented in Table 1. The design differs between the two locations. In Höör, the latest generation of turnouts (EV-60E) featuring rail fastenings with a soft resilient element (rail pad) between crossing rail and sleepers is installed, while Stehag and Vätteryd feature an older design (UIC60) with a direct and very stiff connection between crossing rail and sleepers.

The geometries were scanned using the high-precision Creaform HandySCAN 3D laser scanner, see Figure 10. During the in-situ scanning, additional reference objects were mounted on the crossing rail to increase the quality of the scan. The properties of the scanner are given in Table 2. Examples of a processed geometry scan and prepared 2D crossing rail profiles for MBS analysis are given in Figure 11 and Figure 12.

Table 1 Crossing panel data.

Location	Höör	Höör	Stehag	Stehag	Vätteryd	Vätteryd
Crossing name	21B	22A	21A	21B	102	131
Design	EV-60E 1:18.5	EV-60E 1:18.5	UIC60 1:18.5	UIC60 1:18.5	UIC60 1:18.5	UIC60 1:18.5
Direction	Trailing	Facing	Facing	Facing	Trailing	Facing
Radius	1200m	1200m	1200m	1200m	1200m	1200m
Crossing rail installation date	2014	2014	2018	2012	2014	2014
Scanning date	2019-06-04					

(a)

(b)

Figure 10 (a) 3D geometry scan of a crossing rail, (b) Creaform HandySCAN 3D laser scanner [30].

Table 2 3D scanner properties.

Scanner information	
Device	Portable 3D laser scanner
Accuracy	0.035 mm
Volumetric accuracy	0.02 mm + 0.06 mm/m
Measurement resolution	0.025 mm
Mesh resolution	0.1 mm
Measurement rate	800 000 measurements/s
Light source	7 laser crosses
Scanning area	310 x 350 mm

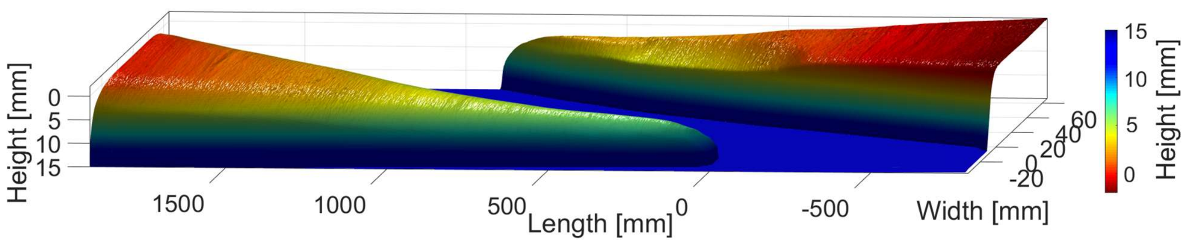


Figure 11 3D scan of crossing nose (left) and wing rail (right).

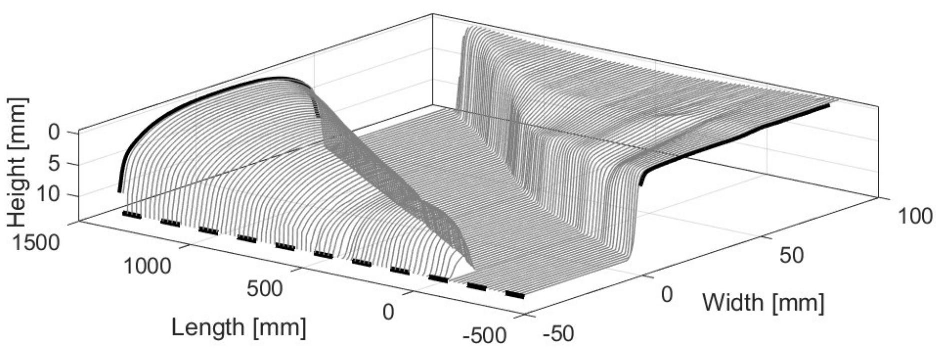


Figure 12 Post-processed 2D cross-section profiles prepared for MBS analysis. The longitudinal spacing between profiles is 10 mm. The crossing nose is on the left and the wing rail is on the right.

3.2 Sleeper acceleration measurements

Two datasets of sleeper acceleration are used in the presented research. The first dataset was obtained during four months of monitoring of eight crossing panels, from September 2017 to January 2018. This dataset contains approximately 100 000 train passages. The second dataset concerns six crossing panels and one week of monitoring in June 2019. This dataset contains approximately 600 passages from X2 high-speed passenger trains. The acceleration data was acquired with sensors from

Konux GmbH, permanently mounted on the sleeper next to the crossing transition (shown in Figure 4). All presented studies used raw data directly from the sensor, for which the properties are given in Table 3.

Table 3 Konux GmbH Accelerometer properties.

Sensor information	
Device	Monoaxial cellular accelerometer
Installation	Permanent sleeper connection
Direction of measurements	Vertical
Sampling rate	2 kHz or 20 kHz
Range	±50g and ±100g

4 Condition monitoring

This section presents a literature survey of notable work in the field of condition monitoring, which has been a foundation to the condition monitoring framework developed and applied in this thesis.

4.1 Condition monitoring field overview

A thorough review on vibration-based damage detection in civil structures is presented in [31]. It overviews traditional methods (58 articles) as well as Machine Learning and Deep Learning methods (54 articles). It is stated that the most successful damage detection systems are those used for vibration-based condition monitoring of rotating machines. The high efficiency of damage detection for such systems lies in the controlled operational environment and the minimal influence from environmental conditions. The given conditions enable feature extraction for early fault detection, see the example given in [32].

Feature extraction for condition monitoring is usually carried out in the frequency domain by identifying and observing changes in eigenfrequencies and eigenmodes of the structure. This can be approached as a black-box type of condition monitoring with a binary outcome (healthy or damaged) or damage index, or as a white-box condition monitoring by observing the evolution of physical damage. Additionally, when these two approaches are combined, it is referred to as grey-box condition monitoring.

Considering feature extraction in the frequency domain using the white-box approach, a variation of 14-18% was noted for the first four eigenfrequencies of the healthy Z24 bridge in Switzerland merely due to changes in environmental conditions [33]. This change was concluded to be much larger compared to the influence that typical physical damage might introduce. Thus, with the black-box approach, difficulties would be encountered in blindly detecting damage from extracted features, as the influence of damage on them is smaller than the influence from changes in environmental and operational conditions. In [34], for a bridge monitored over 10 years, the authors showed examples that nonlinearity and damage could lower the dynamic response, and also that the eigenfrequencies of the structure were significantly influenced by the environmental conditions. In this case, feature extraction of eigenfrequencies and eigenmodes can encounter superposition of the influences from damage and environmental conditions such that the total response could fit the nominal conditions. These challenges are being addressed in the field in various ways, but the mentioned examples particularly suggest that significant domain knowledge of the mechanical system is required when designing a condition monitoring system, so that that the actual damage indicators can be monitored.

Additionally, notable structural health monitoring work in the domain of operational modal analysis and stochastic subspace system identification is presented in [35-37]. There an assumption is made that the system excitation is random, but it is concluded that the identification of damage is dependent on the covariance of the assumed random excitation. This can also mask the identification of damage (as in the previous examples) as the environmental conditions strongly affect the properties of the assumed random excitation.

Considering the ambition to detect small damage at an early stage, it is not found in the literature (by the knowledge of authors) that system identification methods can reliably achieve this goal in harsh operational conditions with unknown excitation. For the application of condition monitoring in railway crossing panels, with variable unknown load and changing environmental conditions, this suggests that the early stages of the development of a condition monitoring system should focus on isolating independent damage signatures. Robust feature extraction approaches could be included in later development stages when it is clear what the relevant form of damage is and what its signatures are.

Concerning structural health monitoring in the railway industry, a comprehensive overview can be found in [38, 39]. A particularly interesting statement for this thesis is found in [38], where the authors state that there is little information on the processing of acceleration recordings in the literature as the authors of those research papers hold interest in the methods they describe. Thus, this thesis addresses one of the identified problems in the field by developing and presenting in detail signal processing tools for condition monitoring where acceleration measurements are being used.

Additionally, an important aspect of condition monitoring is the design of an acquisition system that can successfully capture the relevant dynamic response. In this thesis, accelerometers are used with sampling rates 20 kHz (Paper A) and 2 kHz (Paper B). One of the presented observations is that changes in ballast stiffness are primarily observed via changes in the quasi-static track deformation at low frequencies, while changes in the crossing rail geometry can primarily be observed in the dynamic track response at higher frequencies. In [40], it was found that the quasi-static track response is dominated by track deformation wavelengths above 1 metre. Thus, this is utilised as the separation line between the quasi-static and dynamic response. At a typical passenger train speed of 160 km/h, a one-metre wavelength corresponds to a frequency of 44 Hz.

In this thesis, for the reconstruction of sleeper displacement from sleeper acceleration, low frequencies down to 0.2 Hz have been observed to be important. Contrasting this to different types of sensors used in railway condition monitoring, it is pointed out in [39] (from 2015) that geophones have a high cut-off frequency of 4-12 Hz and are limited to a high frequency of 1 kHz. Thus, this type of geophones would not be able to successfully capture the crossing behaviour in the low-frequency domain. In [41], the authors used optical sensors to monitor railway traffic achieving a sampling rate for a strain profile of 31.4 Hz. Considering a quasi-static track deformation frequency domain with an upper-frequency limit of 44 Hz for train passages at 160 km/h, this sampling rate would not be sufficient for capturing the deformation profile. It is also important to note that signals excited by train passages are highly transient and that the Nyquist rate [42] is not a proper reference for choosing the appropriate sampling rate. For the application in this thesis, it is suggested that the upper bound of the monitored frequency domain should be at least eight times oversampled. This gives eight sampling points per wavelength for the highest considered frequency. For more information on railway vibrations, [43, 44] are sources of domain knowledge regarding railway track and subgrade vibrations and provide an overall benchmark on railway vibrations.

4.2 S&C condition monitoring framework

In general, approaches for condition monitoring and structural health monitoring for damage detection involve 1) defining the damage, 2) establishing the sensing and data acquisition and 3) post-processing and analyzing the measurements. The crossing panel system studied in this thesis fits this context of damage detection and condition monitoring as it includes different 1) damage definitions, 2) types of sensing and data acquisition, and 3) methods that analyse the measurements. In this thesis, a white-box framework has been chosen using time-domain physical models. Two types of damage are addressed: the degradation of crossing rail geometry and the degradation of ballast support conditions. Also, two types of data are acquired: 3D crossing rail geometry scans and crossing sleeper acceleration measurements. The applied methods for analysing the data are based on signal processing of sleeper accelerations, and simulations using the 3D rail geometry scans in an MBS model that has been calibrated based on sleeper acceleration responses. Both the sleeper acceleration data and MBS analyses address condition monitoring by estimating the operational behaviour of the crossing panel. Overall, in the literature survey for S&C presented in Section 2.6, condition monitoring methods addressing the condition of the unloaded crossing panel were found [20, 21]. In contrast to this, for example in [25], it is stated that a new crossing undergoes initial rapid rail damage due to the adaptation to multiple train wheel profiles. In this case, just by observing the unloaded crossing panel with crossing rail changes, one could conclude that the crossing rail should be restored to the unused (as new) state. This could restore the system to a higher degradation rate. Additionally, condition monitoring may be performed with an axle box accelerometer [45]. The limitation of this approach is that it only addresses the operational behaviour of the crossing panels considering the dynamic response of a specific type of train wheels and running gear.

In conclusion, this work emphasizes operational kinematics to monitor the condition of the crossing panel. In Figure 13, the developed condition monitoring framework is presented. It features four levels of condition monitoring. The framework is built from measurement data analysis guided by numerical analysis. The online condition monitoring data consists of sleeper accelerations that are reconstructed to sleeper velocities and sleeper displacements. At the lowest level, the reconstructed sleeper velocities are qualitative condition indicators for track support conditions as when sleeper (track) displacements increase (observing bogie passage signature) they also increase. Further, the reconstructed sleeper displacements are quantitative indicators of track support conditions (considering the low-frequency contents) and quantitative indicators of crossing rail geometry state (considering the high-frequency contents). Thus, the processing of measured and reconstructed sleeper dynamic responses concerns both the low and high-frequency domains. The monitored and processed data is stored for further statistical analysis based on trends history, and as data for calibration of MBS models. The calibrated MBS models are used for diagnosis, and for state extraction to allow additional statistical analysis of trends over time. The last step of the framework (future work) concerns damage evolution modelling based on calibrated MBS models and service life predictions.

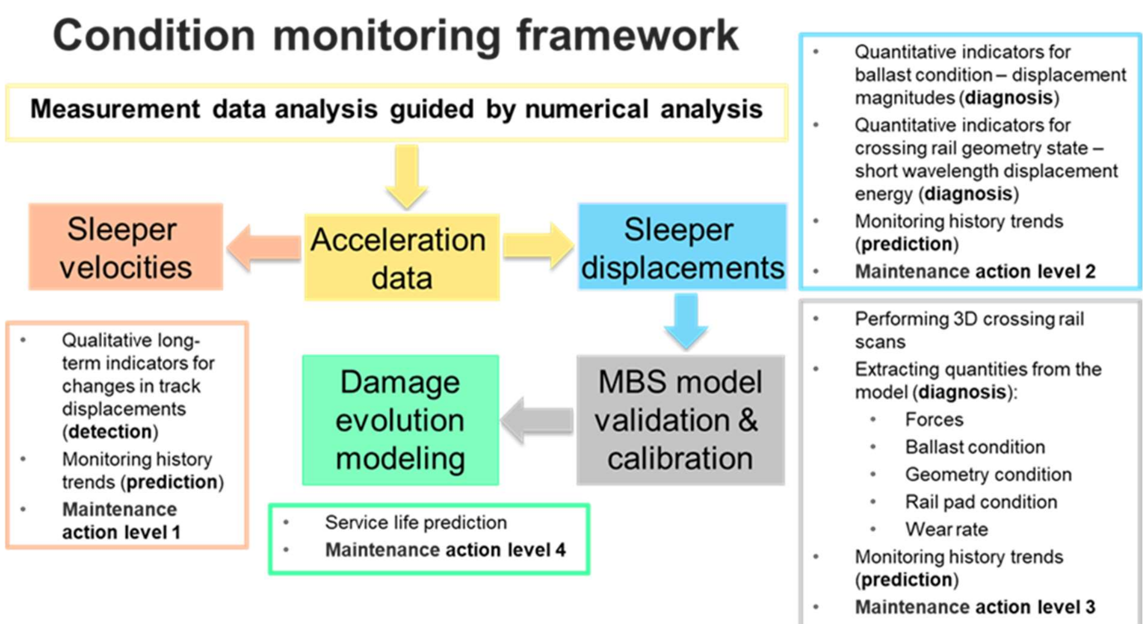


Figure 13 Condition monitoring framework concerning measurement data analysis guided by numerical analysis with four levels of maintenance action possibilities.

5 Summary of appended papers

Paper A: Reconstruction of sleeper displacements from measured accelerations for model-based condition monitoring of railway crossing panels

This paper addresses method developments for online condition monitoring of crossing panels based on operational acceleration measurements. The focus of the work has been guided by two identified gaps in the literature on S&C condition monitoring: The lack of a methodology that 1) specifically addresses the signal processing aspect of S&C condition monitoring, and 2) sets S&C operational condition monitoring evaluations in the perspective of the railway network and demonstrates a robust large scale processing of measurement data.

The analysis has been performed based on sleeper acceleration measurement data generated by 100 000 train passages in eight crossing panels. Based on the given data, a novel frequency-domain displacement reconstruction method is developed and the robustness of the method accounting for large operational variability of the measured data is demonstrated. To identify individual train types and obtain better information about the operational loading in the condition monitoring data, a train type and speed identification algorithm is developed. The presented condition monitoring framework is completely automatized from the dataset of measured accelerations to the final post-processed long-term results. To aid the interpretation of the measured results, a parameter study has been performed based on MBS simulations of the dynamic vehicle–track interaction in the crossing panel.

Paper B: Condition monitoring of railway crossing geometry via measured and simulated track responses

This paper addresses method developments for model-based condition monitoring of crossing panels based on an MBS model that has been calibrated using scanned crossing rail geometries and measured sleeper accelerations. For the scanned crossing rail geometry, a scheme is presented for the processing of the scanned data. Crossing rail geometry scans have been performed for six crossing panels, while the measured sleeper accelerations (concurrent in time with the geometry scans) contained about 600 passages of the X2 high-speed passenger train (100 per crossing). Based on the frequency-domain displacement reconstruction method from Paper A, sleeper displacements are reconstructed from the measured sleeper accelerations. The MBS models, one for each crossing panel, are calibrated based on these reconstructed sleeper displacements. The calibration scheme includes the tuning of linear or bi-linear (sleeper void model) ballast properties, rail pad properties, and introducing a simplified model of damage to the rails. The results show excellent to good agreement between measured and simulated displacements.

Based on the MBS model with nominal input data for each track parameter, different geometry condition indicators are computed using 19 different wheel profiles, three of which are hollow worn. Additionally, indicators for the condition of the ballast and the crossing rail geometry are introduced: sleeper displacement magnitudes in the low-frequency domain, and the root mean square of sleeper dynamic response (displacements, velocities, and accelerations) band-pass filtered in the high-frequency domain.

References

[1] R. Skrypnyk, U. Ossberger, B.A. Pålsson, M. Ekh, J.C.O. Nielsen, Long-term rail profile damage in a railway crossing: Field measurements and numerical simulations, Wear, 472-473 (2021).
[2] A. Cornish, Life-time monitoring of in service switches and crossings through field experimentation, PhD thesis, Imperial College London, 2014.
[3] W.-J. Zwanenburg, Modelling degradation processes of switches & crossings for maintenance & renewal planning on the Swiss railway network, PhD thesis, Swiss Federal Institute of Technology Lausanne, 2009.
[4] Railway Handbook, Energy consumption and CO 2 emissions focus on passenger rail services. International Energy Agency (IEA) and International Union of Railways (UIC), uic. org/IMG/pdf/handb ook_iea-uic_2017_web3. pdf. Accessed Nov, (2017).
[5] O. Piterina, A. Masharsky, Energy Consumption of Rail Baltica Project: Regional Aspects of Environmental Impact, Economics and Culture, 16 (2019) 148-160.
[6] B. Pålsson, Optimisation of railway switches and crossings, PhD thesis, Chalmers University of Technology, 2014.
[7] X. Li, Wheel–Rail Impact Loads and Track Settlement in Railway Crossings, PhD thesis, Chalmers Tekniska Hogskola (Sweden), 2019.
[8] R. Skrypnyk, Long-term rail damage evolution in railway crossings, PhD thesis, Chalmers University of Technology, 2020.
[9] S.O. Erikstad, Merging physics, big data analytics and simulation for the next-generation digital twins, High-Performance Marine Vehicles, (2017) 141-151.
[10] E. Kassa, C. Andersson, J.C. Nielsen, Simulation of dynamic interaction between train and railway turnout, Vehicle System Dynamics, 44 (2006) 247-258.
[11] E.T. Selig, J.M. Waters, Track geotechnology and substructure management, Thomas Telford, 1994.
[12] H. Jenkins, J. Stephenson, G. Clayton, G. Morland, D. Lyon, The effect of track and vehicle parameters on wheel/rail vertical dynamic forces, Railway Engineering Journal, 3 (1974).
[13] A.S.J. Suiker, The mechanical behaviour of ballasted railway tracks, PhD thesis, Delft University of Technology, The Netherlands, 2004.
[14] M. Sysyn, O. Nabochenko, V. Kovalchuk, Experimental investigation of the dynamic behavior of railway track with sleeper voids, Railway Engineering Science, 28 (2020) 290-304.
[15] T. Dahlberg, M. Ekh, J. Nielsen, State-of-the-art study on railway turnouts: dynamics and damage, Chalmers tekniska högskola, 2004.
[16] In2Track, Deliverable 2.2, Enhanced S&C whole system analysis, design and virtual validation, Chapter 3, (2019).
[17] S. Iwnicki, Manchester benchmarks for rail vehicle simulation, Vehicle System Dynamics, 30 (1998) 295-313.
[18] Y. Bezin, B.A. Pålsson, Multibody simulation benchmark for dynamic vehicle-track interaction in switches and crossings: Modelling description and simulation tasks. v3, University of Huddersfield https://doi.org/10.34696/s60x-ay18, (2019).
[19] J.J. Kalker, A fast algorithm for the simplified theory of rolling contact, Vehicle System Dynamics, 11 (1982) 1-13.
[20] K. Wang, W. Cao, L. Xu, X. Yang, Z. Su, X. Zhang, L. Chen, Diffuse ultrasonic wave-based structural health monitoring for railway turnouts, Ultrasonics, 101 (2020) 106031.

[21] M. Sysyn, U. Gerber, O. Nabochenko, D. Gruen, F. Kluge, Prediction of Rail Contact Fatigue on Crossings Using Image Processing and Machine Learning Methods, Urban Rail Transit, 5 (2019) 123-132.
[22] X. Liu, V.L. Markine, H. Wang, I.Y. Shevtsov, Experimental tools for railway crossing condition monitoring (crossing condition monitoring tools), Measurement: Journal of the International Measurement Confederation, 129 (2018) 424-435.
[23] I.A. Khouy, P.-O. Larsson-Kråik, A. Nissen, J. Lundberg, U. Kumar, Geometrical degradation of railway turnouts: a case study from a Swedish heavy haul railroad, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 228 (2014) 611-619.
[24] B.A. Pålsson, J.C.O. Nielsen, Dynamic vehicle-track interaction in switches and crossings and the influence of rail pad stiffness - Field measurements and validation of a simulation model, Vehicle System Dynamics, 53 (2015) 734-755.
[25] U. Oßberger, W. Kollment, S. Eck, Insights towards Condition Monitoring of Fixed Railway Crossings, Procedia Structural Integrity, 2017, pp. 106-114.
[26] M. Mishra, J. Odelius, A. Thaduri, A. Nissen, M. Rantatalo, Particle filter-based prognostic approach for railway track geometry, Mechanical Systems and Signal Processing, 96 (2017) 226-238.
[27] In2Rail, Deliverable 2.4, Embeded & integrated sensors: System design selection, 2018.
[28] C. Stenström, J. Lindqvist, F. Andersson, Condition based maintenance using MEMS accelerometers: For faster development of IoT in railways, Infra Sweden, 2030 (2017).
[29] L. Xin, V. Markine, I. Shevtsov, Numerical analysis of the dynamic interaction between wheel set and turnout crossing using the explicit finite element method, Vehicle Syst Dyn, 54 (2016) 301-327.
[30] HandySCAN 3D – BLACK Series, THE TRULY PORTABLE METROLOGY-GRADE 3D SCANNERS, Available from: https://www.creaform3d.com/en/portable-3d-scanner-handyscan-3d, Access date: 2021-05-10.
[31] O. Avci, O. Abdeljaber, S. Kiranyaz, M. Hussein, M. Gabbouj, D.J. Inman, A review of vibration-based damage detection in civil structures: From traditional methods to Machine Learning and Deep Learning applications, Mechanical Systems and Signal Processing, 147 (2021).
[32] L. Wang, Y. Shao, Fault feature extraction of rotating machinery using a reweighted complete ensemble empirical mode decomposition with adaptive noise and demodulation analysis, Mechanical Systems and Signal Processing, 138 (2020).
[33] B. Peeters, G. De Roeck, One year monitoring of the Z24-bridge: Environmental influences versus damage events, Proceedings of the International Modal Analysis Conference - IMAC, 2 (2000) 1570-1576.
[34] S. Maas, V.H. Nguyen, T. Kebig, S. Schommer, A. Zürbes, Comparison of different excitation and data sampling methods in structural health monitoring: Kurita-Albrecht, Civil Engineering Design, 1 (2019) 10-16.
[35] M. Basseville, M. Abdelghani, A. Benveniste, Subspace-based fault detection algorithms for vibration monitoring, Automatica, 36 (2000) 101-109.
[36] L. Mevel, M. Basseville, A. Benveniste, M. Goursat, M. Abdelghani, L. Hermans, On the application of a subspace-based fault detection method, Proceedings of the 17th International Modal Analysis Conference, 1999, pp. 35-41.
[37] M. Döhler, F. Hille, L. Mevel, W. Rücker, Structural health monitoring with statistical methods during progressive damage test of S101 Bridge, Engineering Structures, 69 (2014) 183-193.
[38] D. Barke, W.K. Chiu, Structural health monitoring in the railway industry: a review, Structural Health Monitoring, 4 (2005) 81-93.

[39] G. Kouroussis, C. Caucheteur, D. Kinet, G. Alexandrou, O. Verlinden, V. Moeyaert, Review of trackside monitoring solutions: from strain gages to optical fibre sensors, Sensors-Basel, 15 (2015) 20115-20139.
[40] D. Milne, A. Masoudi, E. Ferro, G. Watson, L. Le Pen, An analysis of railway track behaviour based on distributed optical fibre acoustic sensing, Mechanical Systems and Signal Processing, 142 (2020).
[41] A. Minardo, G. Porcaro, D. Giannetta, R. Bernini, L. Zeni, Real-time monitoring of railway traffic using slope-assisted Brillouin distributed sensors, Applied optics, 52 (2013) 3770-3776.
[42] H. Landau, Sampling, data transmission, and the Nyquist rate, Proceedings of the IEEE, 55 (1967) 1701-1706.
[43] K. Knothe, Y. Wu, Receptance behaviour of railway track and subgrade, Arch Appl Mech, 68 (1998) 457-470.
[44] D.P. Connolly, G. Kouroussis, O. Laghrouche, C. Ho, M. Forde, Benchmarking railway vibrations–Track, vehicle, ground and building effects, Construction and Building Materials, 92 (2015) 64-81.
[45] A. Chudzikiewicz, R. Bogacz, M. Kostrzewski, R. Konowrocki, Condition monitoring of railway track systems by using acceleration signals on wheelset axle-boxes, Transport, 33 (2018) 555–566.