In2Track3

Concluding Technical Report

Edited by Anders Ekberg and Pernilla Edlund

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In2Track3, Cost-efficient and reliablehigh-capacity infrastructure

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ABOUT IN2TRACK3

Background

The European railway industry faces major challenges due to increasing volumes of transportation over time in combination with ageing infrastructure assets. This, and the limited time available for maintenance drives a need for more efficient monitoring and maintenance methods to enhance the performance of European railways.

In order to tackle these challenges, a European research program, Shift2Rail, was set up. The program was aiming at "through railway research and innovation, delivering the most sustainable, cost-efficient, high-performing, time driven, digital and competitive customer centred transport mode for Europe". In order to fulfil this aim, six Innovation Programs (IPs) were set up, with a number of projects in each program. In2Track3 is part of Innovation Program 3 (IP3) "Cost-Efficient and Reliable High-Capacity Infrastructure", and is the concluding project in the series of projects commencing with In2Rail, followed by In2Track and In2Track2.

The project time was 36 months, starting in January 2021 and ending in December 2023.

Project objectives

The general Shift2Rail objectives are

To enhance the existing capacity fulfilling user demand

To increase the reliability delivering better and consistent quality of service

To reduce the life cycle cost increasing competitiveness of the European rail system and the European rail supply industry.

In2Track3 and the In2Track series have continuously progressed towards those objectives by developing technology and technology demonstrators specifically for the track, switches and crossings (S&Cs), and bridge and tunnel assets. Work has been divided into five technical work packages (WPs), corresponding to five of the eleven Shift2Rail Technology Demonstrators (TDs) in the third Innovation Program:

TD3.1 – WP1 Enhanced Switch & Crossing System: Improve the operational performance of existing S&C designs, through delivery of S&C system with enhanced Reliability, Availability, Maintainability and Safety (RAMS), LCCs, sensing and monitoring capabilities, self-adjustment, noise and vibration performance, interoperability and modularity.

TD3.2 – WP2 Next Generation Switch & Crossing System: To provide radical new system solutions that deliver new methods for directing trains to change tracks with the aim of increasing capacity, while reducing maintenance needs, traffic disturbances and life cycle costs.

TD3.3 – WP3 Optimised Track System: Improve the operational performance of existing track designs and explore innovative solutions, by challenging railway system design parameters and associated track construction assumptions currently implicit in track design, and to explore how innovative solutions in the form of products, processes and procedures can provide higher levels of reliability, sustainability, capacity and Life-Cycle Cost (LCC) savings.

TD3.4 – WP4 Next Generation Track System: Improve drastically the track system with higher performance, by demonstrating a step-change in track system performance, targeting a time horizon some 40 years beyond present state-of-the art.

TD3.5 – WP5 Proactive Bridge and Tunnel Assessment, Repair and Upgrade: Improve inspection methods and repair techniques to reduce costs, improve quality and extend service lives if possible. Improved knowledge on bridge dynamics is also a prioritised objective.

Participants

25 project member companies and an additional 14 associated partners from 10 different countries participated in the project (see figure below).

The partners involved are infrastructure managers, technology developers, research institutes and universities, which gives a wide representation of the railway sector as a whole.

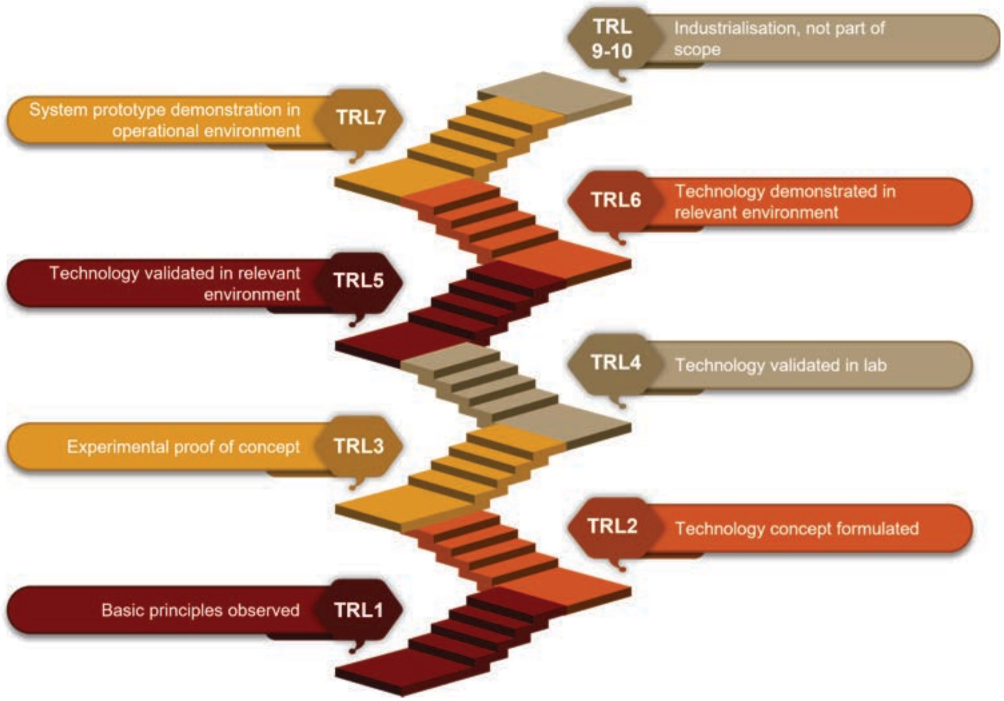
The project was coordinated by Trafikverket, the Swedish Transport Administration.

In2Track3 map of partner countries

Dissemination of results

Results come in many different shapes; most obvious might be a physical installation in track that is possible to see, but results are also incremental improvements of an algorithm for better predictions (for example of life cycle costs), or an improved method (for example for maintenance tasks).

The readiness level of research and development is in the Shift2Rail projects measured using the concept of Technology Readiness Level (TRL), an adaptation by EU Horizon 2020 program of the levels originally developed by NASA. Here, research striving towards physical installation in track are typically straight-forward to grade, whereas algorithms and methodologies are challenging.



TRL levels as defined by the European Union

The projects in the In2Track series have evolved up the scale, starting at lower levels and ending up with quite a few products that are at a maturity level ready for industrialisation and introduction to the market (see Demonstrators section).

Of In2Track3's 50 demonstrators, 25 ended up at TRL7, 7 on TRL6, 11 on TRL5 and 7 below TRL5. 18 of the demonstrators are presented in the Demonstrators' section.

Demonstration activities are a priority within Shift2Rail, as they enable the entire rail sector to visualise and concretely test the transformations that they are able to bring about. They also enable a more appropriate quantification of the impact of each new technology (either alone or combined with other innovations). Demonstration activities also help provide a first estimate of the anticipated potential for sector improvement as a result of the developed innovations.

Three webinars were held to disseminate project results;

- Vegetation management in railways
- Axle box acceleration measurements
- Digital twin solutions for railways

In addition, a number of videos are available to the industry and public, showing high TRL level results demonstrated in operational tracks.

For some of the In2Track3 demonstrators on TRL7, plans for further exploitation were set up. Part of this work was to identify the barriers for the demonstrator to become a product on the market, and give suggestions on how these barriers could be overcome.

Railway industry is regulated by strict security measures, and it can therefore be challenging to introduce new or changed products to the market.

Tackled challenges

In order for the railway to be competitive against other means of transportation, continuous improvement is crucial. Not only do trains need to run faster and carry higher axle loads, but taking the train also has to be cheaper with smaller environmental footprint and with increased reliability and safety for goods and passengers.

This is a challenge, not only for the train operators but for the whole railway sector. The European railway infrastructure is ageing and not always up to the future standard requirements, or even the requirements of today. Replacing existing railway with new state-of-the art railway is not an option, due to high costs and large short-term disturbances and disruptions of the railway that it will cause.

It is therefore necessary for the railway industry to have high focus on methods for predicting failures, monitor assets, mitigate failures that do happen and repair the infrastructure to avoid unnecessary downtime.

In this context, the In2Track3 project focuses on the track structure in a broad sense. This includes topics such as bridge and tunnel monitoring and repair techniques, vegetation management along the track, and maintenance prediction and planning.

The overall challenges related to railways from In2Track3's track perspective essentially boil down to designing a track optimised for its purpose, operating it in a sustainable manner, and optimise its maintenance. What complicates this challenge considerably is that "optimisation" relates to a large set of features. As an example, a robust design can be obtained by making components excessively strong. This would however increase costs and environmental footprint. Consequently, there is a need to understand consequences of design (and operational, and maintenance) decisions on the end results in terms of costs, environmental footprint, performance, robustness etc. To develop, test, and exploit methods to this end has therefore been a key aim of In2Track3.

The research in In2Track3 targets topics setting out from fundamental research related to questions where it is of profound importance to understand the phenomena. Examples are welding bainite (chapter 66) and rolling contact fatigue crack growth (chapter 49).

At the other end of the spectrum are studies that provide validation that the solutions are operational. Many of these are presented in the Demonstrator section.

Another division of the project is into five areas of major importance:

Control - How can we improve assessments of the status of the railway? How do we detect and categorise faults? How do we ensure that operations are safe?

- Robot underwater monitoring (chapter 58)
- Detection of rail level defects using the EMAT method (chapter 22)
- Influence of wheel tread characteristics on operational lives of rail and running gear (chapter 44)
- Sub-surface inspections in tunnels (chapter 69)
- Tunnel structural monitoring using fibre optics (chapter 55)
- Limit criteria for bridge dynamics and proposal for improved bridge design philosophy chapter 59)
- Risk management for track buckling (chapter 24)
- Scour monitoring (chapter 70)

Improve design - How can we improve the design to limit loads, increase strength, and decrease deterioration?

- Improved shear capacity of railway bridges (chapter 76)
- Adaptable and tailored tunnel lining (chapter 56)
- Bridge damping and resonance (chapter 61)
- Design of transition zones (chapter 16)
- Higher precision requirements for slab track structures (chapter 14)
- Radical new tramway crossing (chapter 10)

Predict behaviour - How can we predict the deterioration of the railway so that we can plan and optimise maintenance, and ensure actions are taken before safety issues or traffic disruptions occur?

- Impact of rail rolling contact fatigue (chapter 43)
- Monitoring and prediction of S&C condition (chapter 4)

Mitigation - Based on the identified status and the predicted evolution, what are efficient actions to restore or improve the status?

- Discrete defect repair of rail (chapter 36)
- Replacement of damaged tunnel lining (chapter 74)
- Enhancement and demo of tamping parameters (chapter 78)
- Urban grinding machine to reduce noise and vibration (chapter 73)
- Rail repair by cold spray additive manufacturing (chapter 35)
- Improved welding techniques (chapter 37)

Improved environment - How can the railway limit noise and vibrations in a situation when traffic volumes increase? How can the railway adapt to climate changes?

- Drainage management system (chapter 31)
- Mitigation of noise and vibrations (chapter 51)
- Mitigation of ground-borne vibrations (chapter 50)
- Reduce noise after rail machining (chapter 53)
- Predict and mitigate curve squeal (chapter 52)

Benefits from research

From a railway development perspective, the basic research is of little use in itself. In the same way, demonstrators mainly validate only that already developed solutions are indeed working. The main benefit of research therefore often lies in employing basic research to develop new solutions that can, in turn be demonstrated. This has been an important aim of In2Track3 building on earlier work in In2Rail, In2Track, In2Track2, and other projects.

The concept of TRL levels, as discussed earlier, is straight-forward for products, but much more complex in describing research related to processes and procedures. As an example, consider a code developed to evaluate impact loads from damaged wheels (see chapter 44). To assess the TRL level of the code is fairly straight-forward, but to which level even a working code contributes to assessing the severity of damaged wheels is less clear. It is even more difficult to estimate how far the work has reached in establishing operational procedures including updated regulations.

That being said, In2Track3 has contributed with many solutions applied in operations, research progressing the current state-of-the-art in the drive towards implementation, and supporting research required to drive the next phases of development.

In2Track3 is the concluding project in the Shift2Rail series of project commencing with In2Rail. This means that a lot of effort was put into demonstrating operational results of research carried out throughout the projects. However, development will not end with In2Track3: In some areas the research has revealed new questions. In other areas the topic is so complex that "final" answers are far away. However, also in many such areas implementation into procedures and standards is beginning with the increased knowledge we have gained.

This situation is typical for sound engineering and scientific process: employ the knowledge gained while continue to refine it further. The key part of such a process is however proper documentation and quality assurance of the research and development efforts. This book together with the technical reports (Deliverables) in In2Track3 is part of the former. The extensive scientific publishing in peer-reviewed journals (see Appendix: Publications) is part of the latter.

Regarding implementation into codes and standards, it should be remembered that there are significant differences compared to research regarding scope (standards should cover any possible situation, whereas research is very specific and well defined), and level (where codes should provide a safety net, whereas research is cutting edge). The case gets even more complex if you also consider the aim. Here a standard aims to find consensus between all involved parties, whereas research aims to find "the truth". Demonstrators take a middle part here as they aim for a working solution.

From this perspective it may seem questionable how research could support demonstrators or drafting of standards. The strong argument for basing both demonstrators and standards on a solid scientific foundation relates to the robustness: a working demonstrator is working in a particular demonstrator scenario with a specific implementation. An underlying scientific analysis provides input on how it will behave in other scenarios and implementations. In the same way a standard based on a solid scientific foundation not only represents the current consensus, but also motivates why this consensus is sound.

In2Track3 has contributed towards implementation into codes and standards on different levels. Some examples are:

Enhanced knowledge - This relates to essentially all parts of In2Track3 but is also furthest away from inclusion in standards.

Exploring how standards (and legislation) limit development - An example from the project is how current drone legislations limit development, see chapter 12.

Providing input to enhance existing standards - An example is the producing and testing of anisotropic rail steel specimens to provide more realistic tests of rail head material, see chapter 49.

Providing ideas to improve the approach in standards - Two examples from the project are loads from out-of-round wheels and relation to risk of rail break, and slab track design based on more accurate loads and risk of cracks, see chapters 46 and 14.

Providing bases for new standards - An example here is the possibility to improve welding processes using simulations, see chapter 37.

Highlighting the need for new standards - The project has in multiple fields highlighted the need for standards to gain acceptance, and provide comparable results from innovative inspection methods.

At the other end of the spectrum is the operational implementation in demonstrators. Some examples of these are described in section Demonstrators. These physical demonstrators are easy to grasp as operational implementations of project results. More abstract, but not less important are the implementation of non-physical research results. This can relate to numerical codes and improved simulations, as was used to evaluate the 3MB slab track demonstrator (see chapter 16). It can also relate to improved assessment schemes as for track buckling (see chapter 24) or renovation critical areas (see chapter 19). Another example is development of inspection procedures (see for example chapters 20, 22, 57, 58).

Finally, the socioeconomic impact of the project should be mentioned. The In2Track3 project has a budget of close to 30M€. Can this be justified from a socioeconomic perspective? We believe this is the case. One motivation is the on-going long-term increase in railway transportations, a trend that needs to be even stronger to counter environmental impact and congestion. However, as traffic increases on more or less the same network, maintenance and renewal needs to improve to prevent increasingly severe consequences of disruptions.

More concrete examples relate to direct savings by adopting knowledge from In2Track3. As the sums involved in investments and transportation value are huge, even small relative savings sum up to substantial gains. As an example, support in restoring operations after a derailment using an assessment scheme developed in In2Track3 is estimated to have saved at least 10M€. This relates to the implementation of one research result on one occasion.

There are other examples of estimated savings in this book and in the In2Track3 reports. Consequently, our statement that In2Track3 is (highly) profitable stands.

The Shift2Rail program and hence In2Track3 project ended in December 2023. However, work and activitites contiue in other projects and programs, most notably the new program Europe's Rail and its projects Iam4Rail and InBridge4EU.

SWITCHES AND CROSSINGS

1 Monitoring of Switches and Crossings

Asma Ladj, *IRT Railenium*

Background

Railway switch and crossing systems (S&Cs), are important parts of railway infrastructures because of their effect on the system reliability, availability and safety. The complexity of S&C, inherited from the large number of components involved as well as their different types and technologies, makes them vulnerable to different failures. While railway inspections are most often performed manually or visually by qualified personnel, this may not be reliable to accurately diagnose and predict the health status of railway structures. It is thus paramount to deploy more intelligent and robust policies, providing relevant information about the health status of the targeted asset. In such context, real-time and autonomous condition monitoring (CM) is recognised to be a powerful tool to improve S&C systems safety and reliability by detecting and predicting deterioration of assets before causing failures. This reduces human inspection requirements, and prevents costly and disruptive interventions. With advancement in communications and computing technologies, wireless sensor networks (WSN) have emerged. The typical scheme of WSN for CM consists of sensor nodes, base station, and remote server. Sensor nodes are IoT (Internet of Things) devices mounted on boards combining components for collecting, processing, and transmitting data (sensing element, analogue-to-digital converter, memory, microcontroller/microprocessor, communication interface, and a power supply module).

The main goal is to design a condition monitoring system (CMS) for an S&C based on IoT sensors. Given railway application requirements (power consumption, cost, robustness, etc.), an instrumentation plan is established to identify key S&C parameters to be monitored and appropriate sensing technologies required to measure each parameter, determine sensors emplacement and mechanical integration for optimal and reliable capturing of data, and select power supply strategy and communication technologies to be adopted.

Increased knowledge and implementable results

The overall scheme of a sensor network is given in Figure1-1. Sensor nodes are fixed or embedded in different parts of the monitored S&C, to ensure monitoring of both POE (point operating equipment) and tracks degradation due to wheel/rail effects. We can distinguish POE current and voltage sensors, switch blade displacement sensor, accelerometers for switch motor vibrations, accelerometers for sleeper vibrations, accelerometers for train detection, and rail temperature sensors.

Each sensor node is configured to transmit its data to the gateway through LoRa (Long Range), low-power wireless communication technology. After that, the gateway relays the data to the remote platform via LTE (Long-Term Evolution), high-speed wireless communication technology. In addition to LoRa, sensors can use LTE connectivity (based on the 4G network) to send data directly to the platform whenever the monitoring system detects an abnormal phenomenon. Sensor nodes are self-powered (via internal batteries) or through a solar panel linked to the gateway, providing a 12V DC power supply.

In the context of IoT solution, sensor devices have restricted resources. Power consumption is optimised by setting up sensors in sleep mode and waking them up only when measurement

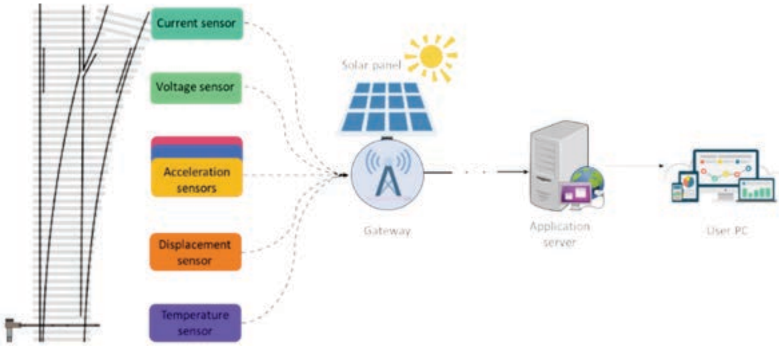


Figure 1-1 Overall scheme of a sensor network

must be done. For motor current, voltage, and vibration sensors as well as switch blade displacement sensor, measurements are triggered whenever the switch motor is activated. When all measurements are collected, data frames are sent to the gateway. Moreover, switch blades positions are checked, and alarm is sent directly to the platform via LTE connectivity if failure is detected (e.g. due to malfunction or ballast obstruction). For sleeper vibration measurements, the sensor is woken up by train approach. For the temperature sensor, a measurement is collected every 2 hours. Collected data are visualised to end-users through web applications.

Implementation and open questions

The objective in this project was to achieve a high TRL (TRL 6). For this reason, the proposed sensor network was manufactured and lab tested. A comprehensive set of laboratory tests has been conducted to validate the operational integrity and evaluate the performance of the system, in a relevant environment. The sensors have undergone rigorous assessments for both environmental aspects (such as autonomy, sealing, resistance, EMC, RoHS compliance, etc.) and functional aspects (including sleep mode, wake-up functionality, measurement accuracy, and communication reliability). Based on successful lab experiments, the system was next installed in real-word environment, on an operating S&C unit. Data is being continuously collected, stored in a cloud server, processed, and visualised through a user platform where different condition indicators are reported.

To leverage the big quantity of data, gathered from the multiple sensors, it would be interesting to develop Machine Learning based models, able to detect and predict S&C failures. This should be advantageous for the optimisation of decision-making regarding S&C predictive maintenance. To achieve that, we can rely on different diagnostic and prognostic algorithms proposed in this project, where an adaptation phase will be preliminary for models retraining and fine-tuning using the collected data.

Deliverable(s): D2.4

2 Repair and replacement of damaged Switches and Crossings components

Johan Ahlström, *Chalmers University of Technology / Trafikverket*

Background

The material in the rail head surface is exposed to high contact stresses in plain rail, but even more in S&Cs due to varying cross sections and impact loads. The wear and tear thus become more critical than on plain rail, and grinding operations are more challenging. Often certain material qualities have to be used, and these are typically prone to other degradation mechanisms than plain rail. The desire to maintain these "hungry assets" in a planned manner, at a low and predictable cost, is the driving force for the work done.

The scope has been to explore and evaluate some possible methods for repairing or replacing damaged parts, find ways to decrease degradation rates of S&C components, optimise the wheel/rail interface using coatings as well as investigating methods for evaluating material performance and component designs.

One track has been to examine 3D printing/additive manufacturing capability for producing replacements of switch and crossing components. Basically, CAD software, topology optimisation software and modern measuring and production techniques have been combined. Failed or worn parts from field were 3D scanned and imported into the CAD software. First the drawings were manually corrected as to restore the original shape, thereafter topology optimisation software was used to manipulate the CAD models to produce suitable components for additive manufacture.

Another track has been to summarise the current requirements on material performance stated in rail norms, identify weaknesses and to develop new methods for assessing the performance in a more realistic loading scenario. Specifically, the excessive shear deformation happening in the rail surface was focused on, and methods were developed to estimate crack growth in such deformed material, resembling how cracks form and grow in S&C components.

Increased knowledge and implementable results

Initially, the idea using 3D printing was to replace bespoke parts not in production anymore. The possibility to start out from a failed part, 3D-scan, restore the geometry via CAD and build it via 3D printing, could save much time and resources. The extended scope was to optimise the design using modern CAD tools including topology optimisation, and the flexibility of the Metal Additive Manufacturing technique. The experiments were successful, but it became clear it was also necessary to adapt to the limitations of the methods and technique, for example to minimise support structures required during printing. The topology optimisation software used is also currently unable to consider fatigue, welds or thermal effects.

The material testing technique developed provided insights into the influence of previous material deformation on the deformation and cracking behaviour. The combination of work hardening and increased anisotropy do change the properties of the material significantly. The most surprising result of the new test method developed, see Figure 2-1, was that the pre-deformation yielded a stronger resistance to deformation, and a higher resistance to crack growth under pure shear loading. This is an important finding, since it proves that the surface deformation of rails and S&C components has a strengthening effect that can be beneficial. However, in field the typical surface cracks observed is evidence this is not the entire truth, cracks typically form in the very surface layer, along the deformed surface microstructure.

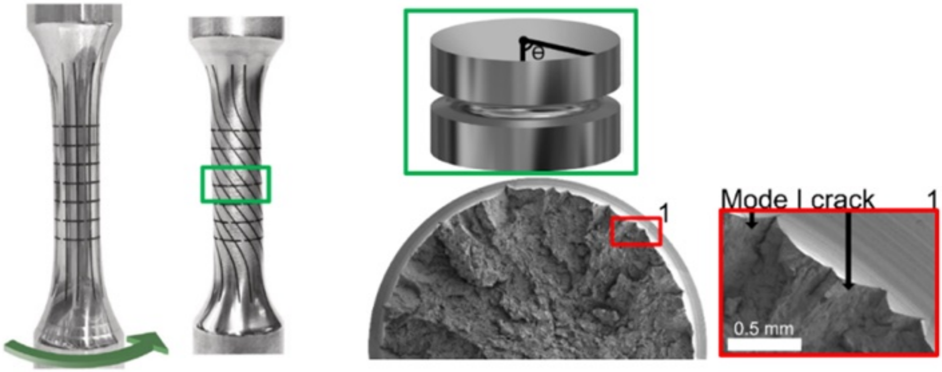


Figure 2-1 The pre-deformation of test bars, a notch machined in the middle section of the test bar, and the fracture surface after torsion fatigue testing (shear loading).

Implementation and open questions

Two topology optimised 3D printed components for railway fastening systems were produced and will undergo various tests to verify if they meet the necessary performance criteria as part of the fastening system. Additional research is needed to determine the base material specification that would satisfy the performance demands of the railway environment, considering the advancements in affordable metals suitable for 3D printing. To validate the application of this technology for manufacturing components for both switch and crossings and plain line track applications, it would be necessary to install examples of 3D printed components in a real-world infrastructure setting, and evaluate their performance over an extended period.

The material test method developed is not yet fully capable of providing a sufficient evaluation of the performance of a material in the complex load environment of S&C components. Further developments will include a more realistic multi-axial loading (axial and shear loading, alternated). A robust set of criteria and laboratory test methods have to be employed in order for a trustworthy material evaluation of S&C components.

Many researchers have contributed to the results briefly summarised in this text, please read more about the different efforts and results in the Deliverable D2.4.

Deliverable(s): D2.4

3 Design of new actuators for a novel track switch (REPOINT)

Roger Dixon, Rama Ambur, Phil Winship, *Network Rail*

Background

Track switches have worked the same way for over 200 years – switch blades are driven from one position to another to set the route the train will follow. If this movement is not fully completed, locked-in place and detected as such, then trains passing over the switch risk derailment. Each of these elements (move, lock, detect) are single elements which when they malfunction will cause switches to "fail" and potentially derail a train.

The approach taken in this project redesigns the locking and moving aspects of the conventional switch. Passive fail-safe locking combined with redundant actuation and sensing were developed. The switch layout was re-imagined through moving the design away from a traditional wedge-shaped length of switch rail to a movable full head section rail to divert trains from one track to another. This enabled these developments and removed the constraints of traditional switch design.

The specific savings and benefits are believed to be significant. They depend on the installation location as the challenges differ between station throats and goods depot/sidings. In general, we seek a combination of benefits including increased operational reliability through improved performance, reduced maintenance costs and inspection requirements. This is done by utilising factors including condition-based maintenance; modular components offering a more compact solution for multiple (>2) route capability which will potentially enable capacity improvements around switches.

An illustration of the novel track switch can be seen in figure 11-1 in chapter 11 where the rail joint design of the REPOINT track switch is discussed.

Increased knowledge and implementable results

The main focus of this work was to further progress the outputs of hazard identification etc. in In2Track2 and develop a mechanical design for a REPOINT active bearer, see figure 1-2. together with design rationale for the primary systems. Actuation concepts were developed and assessed resulting in the selection of an electric motor driven rotary actuator with reduction gearbox, around which the rest of the system was developed.

Nominal system forces for component strength and lifespan were the focus, rather than maximum forces approaches of the previous projects. This enabled the reduction in size of many parts, while retaining degraded

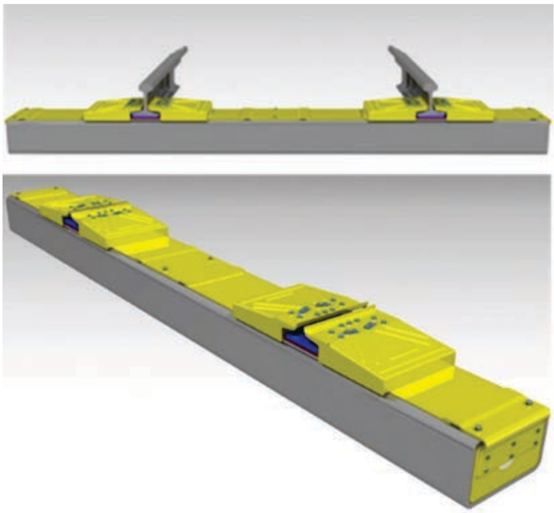


Figure 3-1 Active bearer. Top with, and bottom without rail tips

system functionality, for instance the function will be maintained with just one drive bearer if necessary.

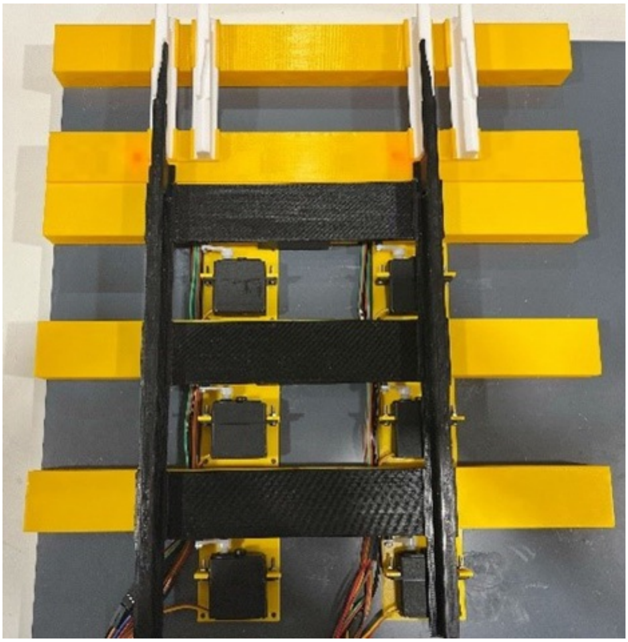


Figure 3-2 Scale Model of REPOINT switch including actuation (modelled using servos)

This design focused on creating a universal active bearer. The aim was to reduce part count, eliminate handed parts and allow one bearer unit to work in any position within the switch and on any turnout geometry.

A UK standard medium switch turnout radius was used for modelling and design. The system allows for compatibility with all turnouts regardless of length.

At the close of the project there are designs for the actuator (as shown in figure 3-1) and the manufactured components of a single actuator element are being assembled for a future laboratory-based test.

A 1:10 scale demonstrator model was also produced (shown in figure 3-2).

Implementation and open questions

There are a number of steps required in order to reach a commercial proposition with this new technology.

The single actuator-bearer will need extensive testing in a laboratory environment. On completion of testing, three actuators and a new REPOINT style track layout would need to be designed and built with a manufacturing partner.

Significant system testing of the new switch panel for repeated actuation will be needed before testing begins in a real-world environment. There are a significant number of tasks that need to be completed before industry can realise the benefits of this game changing next generation switch.

University of Birmingham and Network Rail are actively looking for commercial partners to develop and prove this patented technology.

Deliverable(s): D2.3

4 Monitoring and prediction of S&C condition

Björn Pålsson & Marko Milosevic, *Chalmers University of Technology / Trafikverket*

Background

The annual maintenance cost for the around 12,000 S&Cs only in Sweden has been estimated to be 400 – 450 MSEK (~ 40 – 45 MEUR). These high maintenance costs create a business case for railway managers to employ condition monitoring solutions that could improve maintenance planning and reduce costs and traffic disturbances.

The current practice for monitoring of crossing panels is by manual inspections in track using measurement templates and visual inspection. These inspections can be complemented by data from track recording cars. An alternative solution that has surfaced in recent years is to monitor the track response that follows from the dynamic wheel–crossing transition by using embedded accelerometers mounted on the sleeper adjacent to the crossing transition.

The benefits of this solution are that it allows for continuous monitoring and that the assessment is based on the dynamic response of the structure under traffic loading instead of the system at rest. The challenge that remains, however, is to link the measured accelerations to the physical state of the asset. To this end, this work has been focused on the development of a Crossing Panel Condition Monitoring (CPCM) method that identifies the ballast condition, vertical wheel–rail contact forces and crossing geometry in a crossing panel from measured sleeper accelerations. The main feature of the method is that it uses a simulation model of the monitored crossing panel to derive as much information from a single sensor as possible.

Increased knowledge and implementable results

A flowchart of the developed Crossing Panel Condition Monitoring (CPCM) scheme is presented in figure 4-1. The method takes crossing panel type and measured accelerations as input and outputs ballast stiffness, wheel–rail contact forces and crossing irregularities as condition indicators. The crossing irregularity is here defined as the relative vertical motion between wheel and rail as the wheel rolls over the crossing. By monitoring the evolving crossing irregularity, the degradation of crossing geometry over time can be assessed.

The method was validated by comparing crossing irregularities and forces identified using measured accelerations to crossing irregularities and forces obtained in simulations with the calibrated model and scanned crossing geometries from the instrumented S&Cs. Overall, the method showed good agreement to measurement data for six crossing panels on the southern mainline in Sweden.

The key learning from the project was that this model-based CPCM scheme can identify the requested outputs with good accuracy and shows promise for condition monitoring. The frequency range in which different faults can be studied is however constrained by two fundamental factors. As the sensor is located on the sleeper, the high-frequency wheel-rail interaction is filtered out by the rail pads and cannot be observed.

This means that the global change in crossing geometry can be observed, but not local defects such as spalling or squats. Lower frequency responses cannot be observed either as a sleeper-mounted accelerometer can only observe excitation from wheels in the vicinity of the sensor.

This has no major practical implications, but the acceleration signal needs to be high pass filtered as the low frequency content has too much noise.

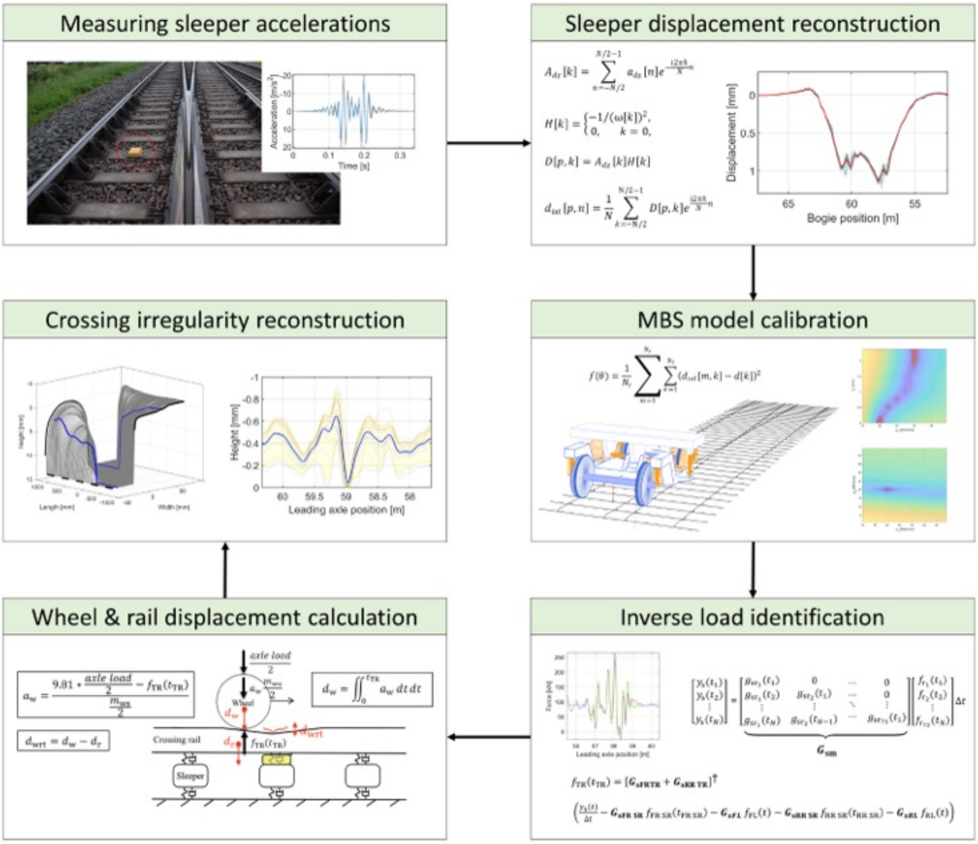


Figure 4-1 Workflow from measured sleeper accelerations to identified ballast stiffness, contact forces and crossing irregularity profile.

Implementation and open questions

The developed method has been published and commercial actors in the field of condition monitoring are free to implement it. The main problem to solve for a large-scale implementation is computational efficiency, as the calibration of the ballast properties is currently performed using multibody simulations. The easiest way around this problem is most likely to pre-calculate S&C models for a range of ballast properties. The model closest to properties of the monitored S&C can then be identified using the sleeper displacement magnitude, and then the identified model can be used for the following steps in the procedure.

Deliverable(s): D1.2 and D1.3

5 Data based models for point operating equipment monitoring

Asma Ladj, *IRT Railenium*

Background

In Prognostics and Health Management (PHM) process, the role of condition monitoring is to continuously collect data through various sensors strategically placed on different components of S&C systems. The huge volume of raw data gathered, on its own and without analysis, has no significant value regarding the health state of the asset under investigation. Instead, monitoring data must be properly analysed to derive useful and meaningful insights for S&C maintenance and performance management. Depending on the consistency of monitoring datasets and the complexity of data processing approaches applied in PHM, different decision support levels can be provided, ranging from simple triggers based on fault thresholds to more sophisticated diagnosis and prognosis capabilities.

While diagnosis involves analysing the current health state of assets to detect and identify potential faults, prognosis, on the other hand, focuses on predicting future asset conditions to estimate the remaining useful life. The integration of diagnosis and prognosis in S&C predictive maintenance enhances decision-making, reduces costs, and contributes to the overall efficiency of S&C systems (minimising downtime, optimising performance, and ensuring the safety and reliability of S&Cs).

Data driven approaches for diagnosis and prognosis of S&C assets are gaining in popularity and a great attention is paid to the success of Artificial Intelligence (AI) field based on machine learning (ML) and deep learning (DL) solutions. In this work, the objective is investigate improving decision making regarding S&C predictive maintenance through the development of efficient and reliable ML and DL methods, able to exploit large amounts of data available from S&C monitoring.

Increased knowledge and implementable results

Since data is at the core of data-driven approaches, the first step is to consolidate enough amount of good quality data. The available S&C monitoring dataset is related to HPSS (high performance switch system) and includes switch engine current consumed during switch rail movements, and switch displacement. Data preparation is then performed. Data cleaning and quality checks involve identifying and correcting errors or inconsistencies in datasets, and ensuring that the data is accurate, complete, and ready for analysis.

To understand switch motor functioning, a data exploration step is carried out. Since the data is not labelled, descriptive analysis and data visualisation techniques, combined with prior knowledge, allow to detect a set of fault types: acquisition faults, operational faults, and unknown faults.

Based on available data, it is not feasible to develop prediction models. Only diagnosis models of switch engine are proposed. To extract useful information from monitoring data, features engineering is applied. Several time and frequency domain features, of different geometric and statistical types, are considered. As the switch operation is characterised by several stages, it is more advantageous to segment data samples and calculate features with respect to each stage.

Unsupervised binary classification is next used to distinguish normal and faulty samples. Values were normalised and empirical tests were carried out to select the suitable features. This binary classification allows us to split the monitoring data into different, well-defined states of the switch system. Thus, data labelling could be done, and more efficient classification algorithms can be developed.

Finally, several multi-classification schemes are developed based on supervised learning: Random Forest, SVM (support vector machine) and ANN (artificial neural network). Good performance is achieved in terms of fault detection and identification accuracy.

Implementation and open questions

The proposed diagnostic models are deployed based on historical data of HPSS units and have shown good performance in term of faults classification accuracy. An interesting perspective would be to apply these models on real data collected by the S&C condition monitoring system developed and installed (In Portugal) within this project. For this purpose, consistent and labelled datasets must be built including clear indications of S&C health states, with various scenarios and potential (naturally or artificially induced) failures, to represent complete "run to failure" data samples. In this case, the development of prognostic models will be possible.

In general, S&C mechanical faults (obstacle, excessive friction, electrical faults, etc.) can be identified through the monitoring of point machine parameters, such as current, voltage, displacement, speed, etc. On the other hand, rail/wheel impacts (plastic deformations, wear, rolling contact fatigue (RCF) defects, etc.) are only detected through the monitoring of rail parameters, such as vibration, sound, temperature, etc., at different parts of S&C panels. Relatively few works address this latter types of faults. Since vibration data are already being collected in field, it would be useful to develop new models able to detect and predict failures induced by rail/wheel effects.

Deliverable(s): D2.4

6 Sensor technology for crossings

Rama Ambur, Phil Winship, *Network Rail*

Background

Switch and crossings are key assets within the track system. Crossings are subject to high dynamic forces when train wheels traverse over the wheel transfer area across the wing rail and nose. These dynamic forces cause wear and damage to occur. The damage increases the height difference between the nose and wing rail resulting in even higher dynamic forces developing, further damaging the crossing. The forces eventually reach a level that the structure of the crossing can no longer withstand, resulting in cracks developing in the crossing body. Once this point has been reached the crossing is not repairable and has to be changed.

In the most severe cases the crossing can break completely across its width resulting in a significant derailment risk and replacement costs.

Currently many the majority crossings are not monitored to assess the acceleration and subsequent forces imparted on the wheel transfer area. The recognition of when to intervene and repair a crossing nose is predominantly done by manual inspection methods and is therefore very subjective and reliant on human factors.

Infrastructure maintainer figures from 2021–2022 suggest that the cost of replacing cracked crossings (excluding installation costs) is around €5m per year.

The measurement of the dynamic forces can highlight when a crossing is at risk of failure. This will allow timely maintenance intervention to prevent a crack from developing and the crossing needing to be replaced.

Increased knowledge and implementable results

A portable system of sensors measuring acceleration and strain was designed (see figure 6-1) and tested in a laboratory environment prior to being installed in a live infrastructure environment.

The sensing unit comprises of accelerometers on the wing rails and on the bearer, together with piezopatches which measure bending strain on the rail foot. The voltage signals from the piezopatches were processed to calculate the strain signals. A data acquisition unit (DAQ) received, processed and recorded the sensor signals. The entire unit was battery powered for ease of installation and is designed to be portable to enable it to be used at various locations as a temporary installation. It can be extended to be powered by a solar panel and can be installed at a safe and convenient location on the track side.

A control unit can activate the entire acquisition in two different modes. One being a manual trigger with a remote, another is an automatic mode with a programmed trigger. The control unit stores the received data in a log file.

The data could either be left on the unit as a backup or deleted. The memory capacity of the control unit is limited so data is transferred to an SFTP server and stored.

The system was installed on crossings of varying age and wear to enable the various stages of a crossing life to be assessed to understand the effect this has on the data recorded.

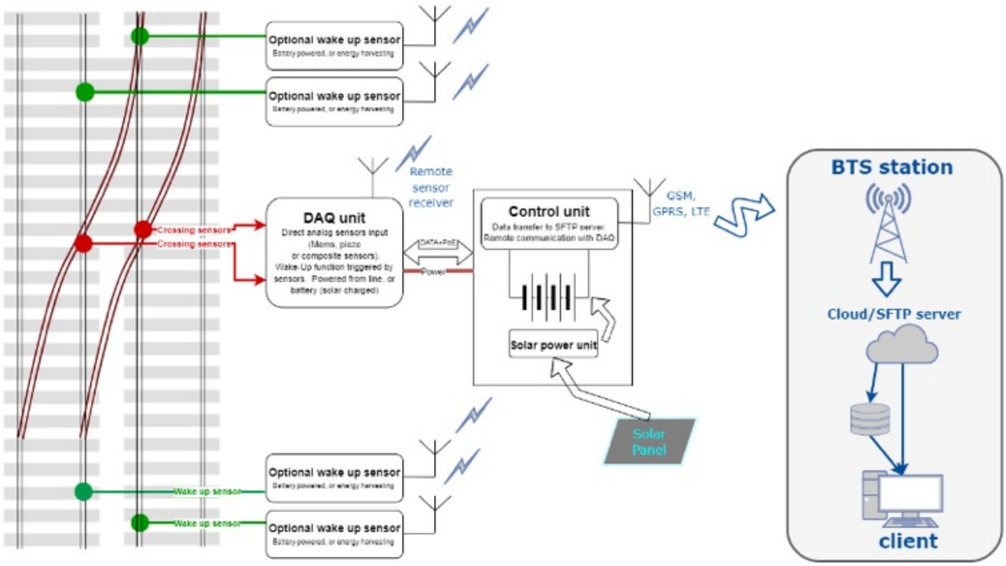


Figure 6-1 Data acquisition architecture

Initial correlation analysis on the sensor signals indicates the presence of redundancy. This is useful in further stages to have a fault tolerant condition monitoring method. Algorithms based on unsupervised learning methods of artificial intelligence technology are under development. They analyse the recorded data to enable this to be translated to assess the condition of the crossing.

Implementation and open questions

Further data capture needs to be undertaken at sites with crossings at different stages of wear to understand how this effects the forces a crossing is subjected to. This data will then need to be analysed to further develop algorithms to enable the condition of a crossing to be accurately assessed.

The research has confirmed that the data recorded can be subject to variability due to a number of factors including crossing angle, vehicle type, speed and tonnage. These parameters will need to be factored into the algorithms developed for the system to ensure an accurate assessment of the condition of a crossing can be achieved.

It is possible to bring redundancy to the condition monitoring by developing at least two algorithms to process the data. The algorithms could use data from separate sensors to ensure that the condition monitoring is safe from sensor failures.

Further work will be undertaken to progress this as a portable solution. This will enable infrastructure maintainers to deploy this system at any site to be able to monitor the forces a crossing is being subjected to.

Deliverable(s): D1.1 & D1.3

7 Development of a digital twin demonstrator for integrated system and sub-system models for S&Cs

Lawrence Tinsley, Khangamlung Kamei, Andrew Starr, *Network Rail*

Background

Under previous work undertaken in In2Track2, a whole-system design for Next Generation Switches and Crossings (S&C) was developed, capturing assessments from rail industry stakeholders on priorities for future development of S&C. Development of the vertical movement filling blocks concept for filling the crossing gap in rail S&C crossings was considered for its potential reduction in leading failure modes and the expected extension of asset life and reduction of whole life cycle cost were modelled. Simultaneously, other projects in In2Track2 developed modelling of S&C components, sections, and novel design features. These included: development of the whole-system concept, development of a system definition for an S&C digital twin. Development of an S&C Digital Twin Framework, a study for implementation of IFC-for-Rail standard 4x3 for BIM, capturing virtual models for Next Generation S&C components, Design and Prototyping of Next Generation S&C Kinematic Systems, and Next Generation S&C Transition zones. Together, these projects outline the shape and key features of digital twin for S&Cs, where their designs, findings and outputs would, once integrated, create a system that can be used to test new components in existing S&Cs, or the development of new concepts with new and existing legacy components; for which, the integration of different models and simulations would be required. Over these projects, a volume of modelling and simulation work has been generated, with many continuing with more advanced modelling taking place under In2Track3. The purpose of a digital twin is to be able to integrate these models, combine their functions, and test them with real and simulated traffic scenarios. While these models overlap in their focus on the same asset (S&C), they do not currently interface directly with each other. In order for a digital twin to be useful to test and develop new concepts and technologies for future asset designs, these disparate models would need to be able to be interfaced in the same software system.

The objective for this project was to develop a means to integrate sub-system models into an S&C 'digital twin', where interactions between the models could be handled in a single interface.

Increased knowledge and implementable results

The project developed a demonstrator user interface for interacting with the virtual models of S&C, primarily focused on the models undergoing further development in In2Track3 sub-task 2.1, capturing the required inputs and available output options, and providing the prospective user with a simplified approach to requesting further interactions; for example, a user without either direct access to (or experience with) one of the virtual models being developed for the S&C vertical movement stub switch (REPOINT), would be able to view the default parameters for a current model setup, and with a simple user interface be able to make selections of parameter changes that would be of interest for re-running the simulation with new parameters, submitting the new parameter set as a 'job request' to the development team in charge of that model. With outputs from the model being returned to the system and stored in its database, these outputs could then be selected using the same user interface, as inputs to other models, for other parts of the S&C.

Microsoft Power Apps was used for development of the system's front-end user interface, which could be used to generate a simulation request with new parameter changes. The app requires a database to contain the parameter options and ensuing data outputs, which was developed in Microsoft Excel. The app is shown with some of its model interaction screens in figure 7-1. Implementation was limited due to few virtual models being available. Furthermore, some limitation for the user of the app to make updates to the database operating behind the app was found, which could be circumvented if the database is hosted outside the app's data tray, on a cloud resource the app could interface with.

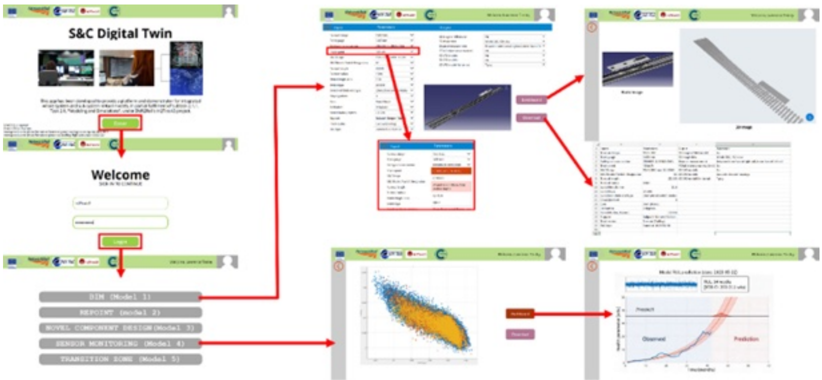


Figure 7-1 The virtual model interaction app user interface, using model example from In2Track2, and MATLAB and Simulink for Predictive Maintenance [https://uk.mathworks.com/solutions/predictive-maintenance.html]

Implementation and open questions

The app provides a demonstrator for a 'Digital Twin' of S&C and how its database may facilitate interactions between the different parameters and types of data, featuring a login screen to safeguard the data contained, a model interaction selection screen, model input/output parameter selection screens for 2 models, and a partial parameter selection screen for a third model, and an output 'job request' function, that generates a simulation 'job request' file, to submit to model developers. The demonstrator requires considerable further development, as many of the models were still undergoing development during the project, and could not be interacted with directly. At the completion of the project, a variety of lessons were learned, for future development of a digital twin of rail S&C:

- An interface for the digital twin can be developed using Microsoft Power Apps, provided the underlying database is instead hosted on a cloud resource.
- Interface between models in different organisations is achievable but requires a client-side app to handle model requests from the digital twin platform.
- Hosting the respective models on a centralised platform would avoid the need for institutional access and manual processing.
- A digital twin developer will require direct access to the models to be integrated.
- Both disparate and centralised configurations would require protection of intellectual property to be implemented.

Deliverable(s): D2.4

8 Whole system modelling for S&C

Björn Pålsson, *Chalmers University of Technology / Trafikverket*

Background

A so-called Whole System Model (WSM) for railway switches and crossings (S&Cs, turnouts) has been under development throughout the In2Track-projects. The objective is that this type of model should allow for holistic simulation-based assessment of S&C designs. There are many models available to study individual damage modes in S&C, but they are generally not able to study the interaction between different damage modes which the WSM is able to do.

In the WSM, dynamic interaction between S&C and passing vehicles is considered along with the loading and deterioration of S&C components over time. An iterative approach is applied where damage increments are computed and accumulated in the model for increments of traffic loading. Given the vast differences in length and time scales involved in dynamic vehicle-track interaction compared to long-term track degradation, it is not feasible for a single model to capture all relevant aspects of long-term S&C deterioration and performance. The WSM is therefore a framework that integrates several state-of-the-art simulation tools and techniques. Depending on the objectives of a given study, the WSM scheme can be tailored for the current task. A schematic representation of the WSM scheme from this task is illustrated in figure 8-1.

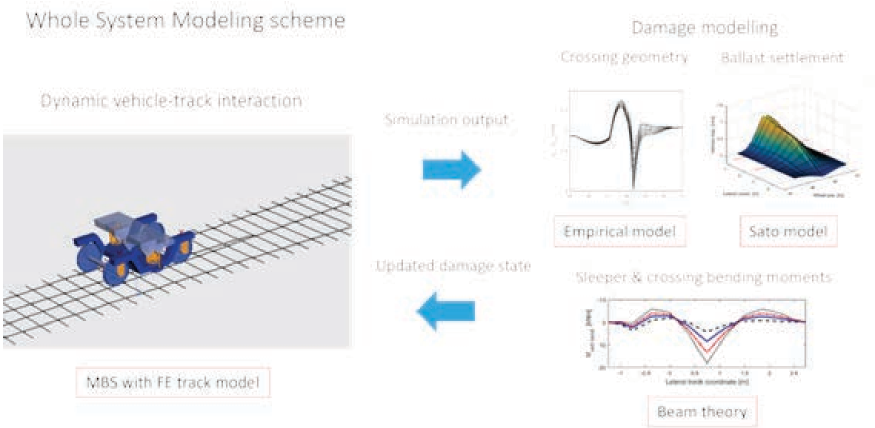


Figure 8-1 Schematic illustration of this version of the Whole System modelling scheme. Simulation of dynamic vehicle-track interaction using multibody simulation with a finite element track model give input for damage modelling that in turn provides damage increments for crossing geometry and ballast settlement before the next iteration.

The main areas of development in this task have been the track model for the multibody simulations and an empirical model to predict the global geometry change for crossings over time. These focus areas were chosen based on the outcomes of the first demonstration of the WSM scheme in the In2Track2 project. There the long simulation times for the crossing damage model as well as the lack of physical sleeper responses due to the simplified track model were identified as the areas with the greatest potential for improvement.

Increased knowledge and implementable results

The developed S&C track model was validated using measurement data from controlled locomotive passages over the densely instrumented Shift2Rail S&C demonstrator in Austria. Using the nominal S&C properties and the scanned crossing geometry as input, the model showed very good agreement to measurements after the ballast properties had been calibrated to the local conditions. The agreement between model and measurements was studied for crossing and sleeper displacements and strains as well as sleeper–ballast contact pressures. One of the key learnings from the analysis of the data from the demonstrator was that a ballast bed can be very uneven also for a newly installed S&C and that it can have a significant influence on the sleeper bending as well as the sleeper–ballast contact pressure distribution.

The calibrated track model was applied to predict long-term damage in the Shift2Rail S&C demonstrator in terms of ballast settlement and crossing geometry change over time using the WSM scheme in figure 8-1. The model could do so with reasonable accuracy in a blind prediction, but as always there are multiple unknown factors about the local conditions making calibration necessary. The WSM scheme used a novel hybrid model to compute crossing geometry change and a threshold model originally developed by Sato for ballast settlement calculations. The crossing damage model is a hybrid model in that it combines empirical data on deterioration rates and patterns from crossings in track combined with simulation studies to scale the measured results based on the traffic and loading conditions.

Implementation and open questions

It is argued that the WSM has reached sufficient maturity to be implemented and address problems in S&C design and maintenance. It is still so, however, that predicting the long-term deterioration of S&C over literally millions of loading cycles is a daunting task with many influencing parameters as well as unknowns. Simplifications are therefore necessary and careful consideration is needed to determine what type of modelling detail is needed to address a given question. It is argued that the main strength in this type of modelling lies in the fact that relative comparisons can be made between different turnout designs or operating scenarios and that design trade-offs can be studied as the WSM can output most of the relevant damage modes in S&C in the form of ballast settlement, crossing geometry damage and changes in structural loading. The biggest scope for improvement in the WSM is the crossing damage model where more empirical data as well supporting simulations should allow for better predictions.

Deliverable(s): D1.2 & D1.3

9 WSM sub-model: Crossing nose

Kamil Pezzutti, *Virtual Vehicle Research*

Background

Railway turnouts feature discontinuities in wheel–rail contact geometry and track stiffness, which cause large dynamic contact forces. These dynamic loads can cause degradation of track geometry as well as rail surfaces. The aim of this work is to develop and demonstrate a novel time-efficient semi-physical plasticity (SPP) model to be implemented into the developed whole system model-based methodology shown in figure 9-1. This is especially important for long-term track condition assessments and can be used for example to optimise design and material selection for turnout crossings.

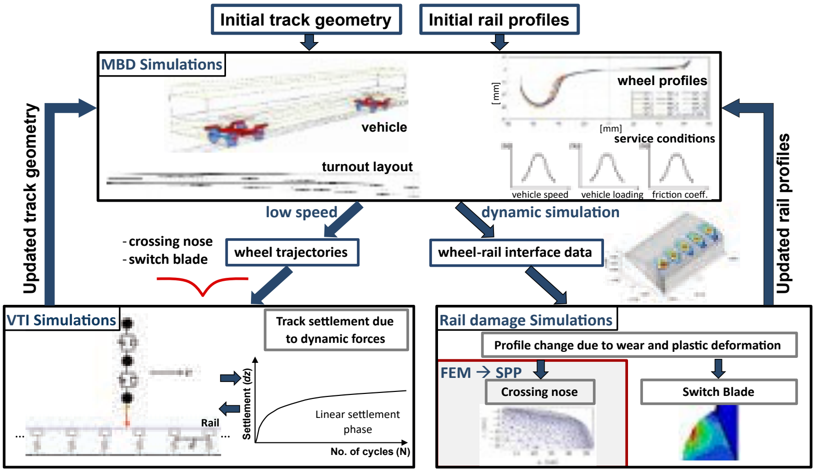


Figure 9-1 Whole system model-based methodology for track damage predictions in railway turnouts.

Increased knowledge and implementable results

The plastic deformation model developed within the project is focusing on the rail profile evolution in the crossing nose region (one of the most loaded areas in railway turnouts) caused by plastic deformation. This phenomenon is dominating during the initial phase after installing a new crossing nose and after maintaining it. The development of the model is based on a dataset generated with a full finite element (FE-) based approach.

Plastic deformation in the crossing nose region is found to be mainly driven by the extremely high contact normal stresses. Therefore, in a first approach, it is assumed that for a given traffic load increment a relationship between mean maximum contact pressure (p0m) and the increment of the shape change area (gs)exists. The results show overall a good correlation between shape change area increments and the mean maximum Hertzian pressure according to the plasticity hypothesis, see figure 9-2.

The second important aspect of the developed methodology is the prediction of the rail profile shape at a given traffic load. Our approach proposes that the shape at a given position develops as an accumulative effect of the wheel profiles envelope taken from multibody dynamics simulations. In other words, at each time step (traffic load) the shape of the rail profiles needs to be the same as the envelopes of the wheel profiles passing the turnout.

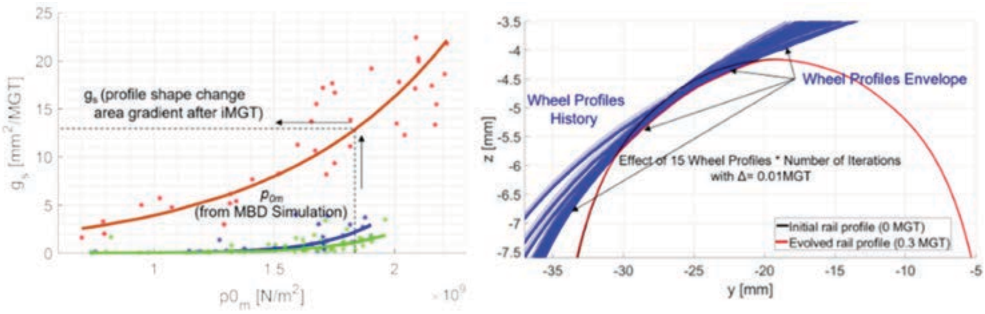


Figure 9-2 (a) Correlation between mean Hertzian contact stresses and profile change area increment from FEM simulations, (b) Rail profile form determination based on the accumulative wheel profile collective effect.

The established model will result in time-efficient predictions of the rail profile changes in the crossing region caused by material plasticity effects. Two chosen cross-sections were selected. One with a good agreement between FE results and the SPP model (CSa) and one with a relatively high deviation (CSb), see figure9-3. For both cross-sections, the maximum error is smaller than 0.5 mm2. By adding the effect of additional influential factors (e.g. consideration of shear stresses) it might be possible to improve these results.

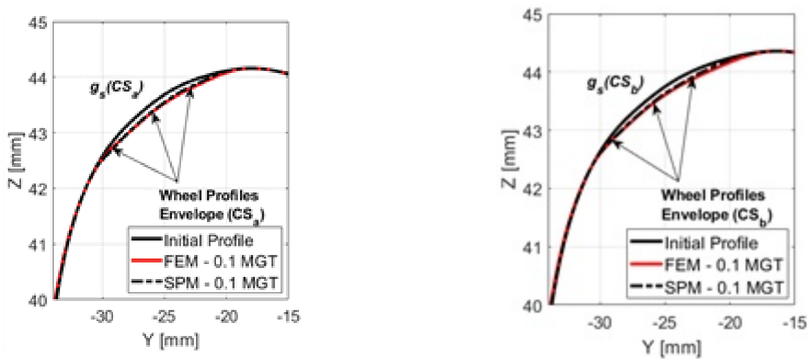


Figure 9-3 Rail profile evolution (FEM simulation results comparison with the SPP model simulation results for the two chosen cross-sections positioned along the turnout).

Implementation and open questions

The simulation results are in good correlation with plasticity calculations carried out in FE analyses for R350HT steel grade. The computational time was significantly improved (order of minutes instead of weeks).

Deliverable(s): D1.3

10 Concentric moveable crossing

Christian Ebner-Mürzl, *voestalpine Railway Systems*

Background

High emission of noise, massive wear as well as high maintenance and serving costs are a huge influencing factor in tramway crossing design. Due to the reason most trams are used in highly populated areas the emission of noise is a big problem.

One factor causing this problem is that the tracks are crossing in one level without tangentially connecting and continuous running edges. Especially crossings with a high angle or a shallow depth groove generate noise and are subject to higher wear.

A basic research and design study as basis for the current development was done in the previous In2Track projects.

Increased knowledge and implementable results

Since the design was validated by the project team, it was decided to build a full-scale prototype of the concentric moveable crossing in order to test it in-field.

Single component tests have been numerically simulated and were tested with pre-assembly tests and fulfilled the needed performance to be assembled in the whole system.

For more convenience the first in-field test will be performed in in-house facilities in North Germany. During the last months vaRS managed to purchase the parts from different suppliers or manufacture the different components of the concentric moveable crossing in-house.

Figure 10-1 First build-up Concentric Moveable Crossing

During the first assembly some tests were performed. Several mechanical component tests were passed for the first release and the start of the prototyping. These resulted in a concentric moveable crossing as depicted in figure 10-1.

Currently the full mechanical component and fully assembled testing is ongoing, where the durability of several components as well as the whole concentric movable crossing are evaluated. To this end, the first demonstrator of the concentric moveable crossing has been assembled and is installed in the field track of voestalpine Germany.

Implementation and open questions

The installation of the concentric moveable crossing contains functional testing in factory track as well as stress testing under real installation conditions. The first step is going to be to test the concentric moveable crossing in the internal track. In the internal track testing two versions of the actuator design will be evaluated and tested.

By this testing in field influences of operational conditions on the concentric moveable crossing are going to be tested and the installation in the real track system can be tried out. Also, the environmental influences like dust or rain can be seen during the operational testing time. The noise of the concentric moveable crossing will be measured and then compared with standard crossings when installed.

Deliverable(s): D2.5

11 Radical new wheel transfer (Repoint joint)

Roger Dixon, Rama Ambur, Phil Winship, *Network Rail*

Background

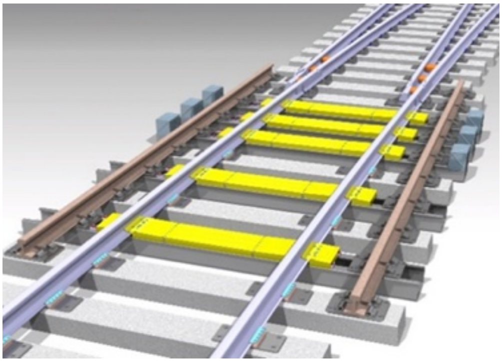


Figure 11-1 A new switch layout including triple redundancy in actuation and a novel stub switch joint.

A standard rail switch incorporates a moveable pair of rails. These are fixed at their heel and have greatest movement at their long-planed blade tip (toe). Our approach to improving this combines passive failsafe locking, with redundant actuation and sensing, and a reimagined switch in a stub layout.

The moveable rails in the stub layout are reversed, being fixed at what would normally be described as the toe and have maximum lateral movement some distance into the turnout radius.

The main focus of this work was examination of the wheel–rail interface forces and accelerations at the joint. In addition, a mechanical design for the REPOINT track switch active bearer with actuators is discussed in chapter 3.

Increased knowledge and implementable results

The main focus has been examination of the wheel–rail interface as trains traverse the rail joint (rail-tips). The initial joint has been designed to be similar to an expansion joint. The joint geometry allows for expansion and positive location (interlocking) between the moving tip (red) with the fixed rail (grey) seen in figure 11-2.

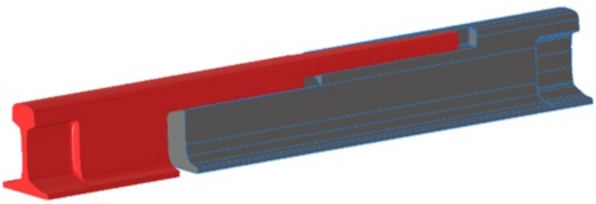


Figure 11-2 Novel rail joint design

In order to predict the performance as vehicles pass over the joint, the complete switch is modelled and subjected to dynamic loads from a representative passenger vehicle in the Simpack multibody simulation environment. The switch joint between the two rails was modelled in both trailing and facing directions (figure 1-3). This joint is unique in its design due to the horizontal and vertical interlock; hence it presents a challenge for modelling and two different methods were verified in the software.

The study explored the transient dynamic forces at the stub joints and wheels, and the deflection dynamics of the track were also studied. Comparison was made to a conventional switch for the same track geometry. The forces and deflections experienced with REPOINT are smaller than the conventional switch, due to the shorter length of the switch and symmetry of the joint on either side of the track.

Based on these predictions, it is anticipated that there is reduced risk of damage to the rail joint and possible derailment utilising the REPOINT switch.

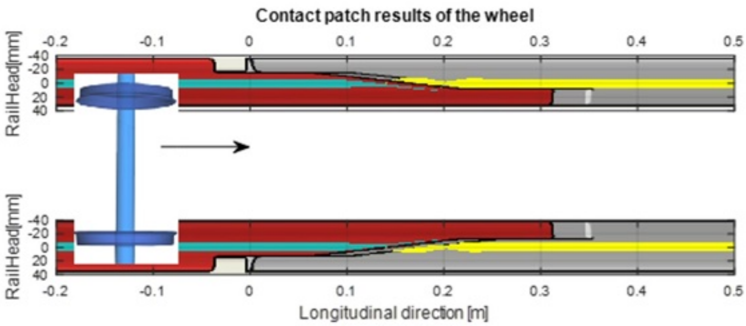


Figure 11-3 Plan view of the REPOINT joint, illustration showing passage of first wheel-set left to right (including contact patch).

Implementation and open questions

There are still several steps required to reach a commercial proposition with this new technology.

The system model makes use of individual component models. Testing in both a laboratory and a track infrastructure environment would be required to validate these results.

After validation of the model, it can be used for comprehensive checks of the joint key design features: e.g. the overlap required, the expansion allowance required; enabling optimisation of the design.

Deliverable(s): D2.3

12 Autonomous inspection of Switches and Crossings using drones

Mark Wakling, Phil Winship, *Network Rail*

Background

Switches and Crossings (S&C) are complicated parts of the railways. The components are subjected to high loads when a train crosses from one line to another, causing wear and damage. To ensure the safety, reliability and performance of the S&C it is vital they are inspected regularly.

Traditionally, a "boots on ballast" approach has been taken to these inspections through manual 'on-track' inspections. An inspector walks through the S&C, visually inspecting the components.

The project proposes a novel approach where the inspection of S&C is undertaken remotely using data collected by a drone. Safe, reliable, cost-effective, and user-friendly drones are now widely available. These drones can carry payloads that can capture rich data, which can be used to give an excellent understanding of the asset in its current state.

A remote inspection removes the need to access the track, improving staff safety while reducing cost, associated carbon emissions, and disruption to train operations. Through machine learning changes within the S&C can be automatically detected. This enables the inspector to focus on the areas where change has been detected, improving the productivity and accuracy of inspections.

Increased knowledge and implementable results

High-resolution imagery is required to inspect S&C adequately. Ground Sampling Distance (GSD) describes the ground area within a single digital image pixel. A GSD of 0.9 mm indicates that one pixel represents an area of 0.9 mm^2 on the ground. Testing showed that this resolution was required to enable a remote inspection. Lower resolution prevented small changes and defects from being visible to the inspector. Achieving this resolution requires high-grade camera payloads optimised for UAV applications.

Change detection is critical to enhancing the experience of the remote inspector. This relies on a high degree of precision between surveys. Poor precision will indicate that change is occurring when nothing has happened leading to a false positive reporting, degrading the inspectors' experience and reducing their confidence in the system.

High-precision outputs require robust survey and photogrammetric data processing practices. When this is achieved the position and orientation of assets relative to a previous survey is known and any change can be detected automatically with several benefits:

Safety – Drones remove the need for an inspector to enter the track environment. Fewer people are required to attend site, reducing the risks and carbon associated with travel.

Cost – Inspectors can undertake inspections in a more productive and safer environment.

Disruption – S&C can be inspected while trains are running.

Implementation and open questions

The solution is now mature and capable of being utilised for regular S&C inspection operations.

Innovation would focus on enhancing the machine learning tools that inform the change detection process. A new approach would focus on detecting change without the need to detect specific assets within the S&C. This would reduce costs and enable this solution to scale without the need for an extensive library of S&C components to be built and maintained.

Finally, further innovation would consider creating an as-built digital twin of the S&C. This would provide a baseline for the components within the S&C along with their specific location and orientation. Each S&C inspection would be compared against the digital twin to understand the changes, with the digital twin acting as the vessel for any recorded information about the components and assets within it.

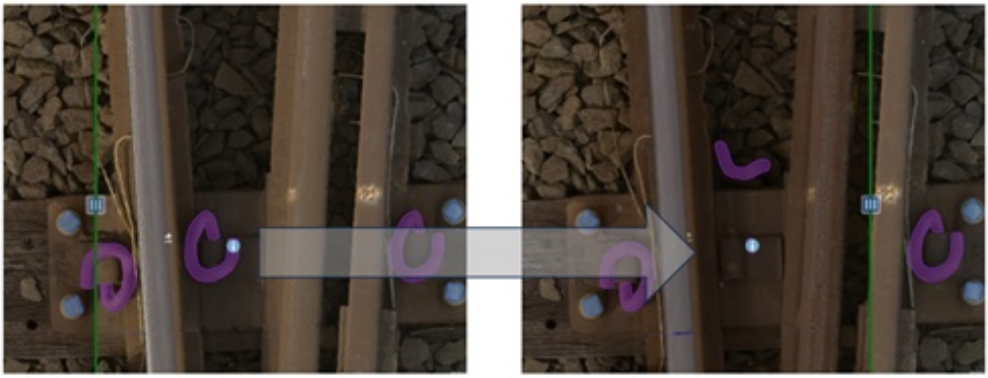


Figure 12-1 These two contain the same assets imaged several weeks apart. Machine learning detects a Pandrol clip. The remote inspector is prompted to review the issue and determine the course of action required to resurrect the issue and return the asset to the correct state.

Deliverable(s): D2.6

13 Crossing restoration machine

Jay Jaiswal, Phil Winship, *Network Rail*

Background

Railway switches and crossings (S&C) experience probably the most demanding operating conditions of all track components which is reflected in the impact of their failure on track availability and infrastructure budget for maintenance and renewal. The UK rail network comprises ~20,000 units of S&C that account for just 5% of the ~ 33,000 km network length but are responsible for 24% of the maintenance and 23% of the renewal budgets. A similar position is also evident in other railway networks.

Although cast Austenitic Manganese Steel (AMS) crossings have served the industry well over many years, their low installed hardness leads to appreciable plastic deformation and even shelling in the early stages of their life, both of which require maintenance interventions. The use of explosive hardened crossings reduces the rate of such degradation. However, weld restoration of deformed and damaged crossings continues to be practised to enhance crossing life. The current manual repair processes have little process control resulting in inconsistencies in repair integrity and longevity. The ever-increasing volume and density of traffic are expected to further increase the rate of degradation of crossings. Hence, the need for innovative, robust, and cost-effective techniques for the restoration of worn and damaged crossings.

The development of equipment and process for automated repair of discrete defects in plain line provided the foundation upon which the operational functionality required for automated restoration of crossings has been developed. The developed Crossing Restoration Machine (CRM) utilises similar techniques of laser profile measurement, milling for standardised excavation, FCAW weld restoration (Flux Core Arc Welding), and milling for precise reprofiling.

Increased knowledge and implementable results

A fully functional unit incorporating the required features of laser profile measurement, temperature sensor, milling tool, and welding has been manufactured to deliver a fully automated process for the restoration of crossings.

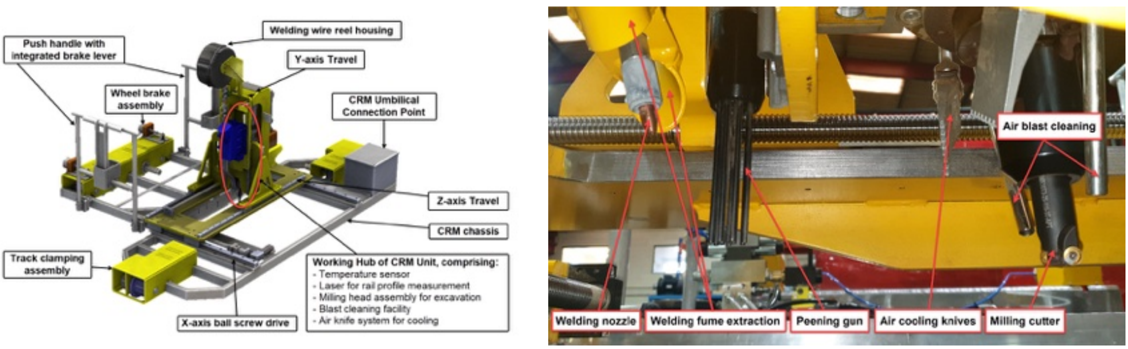


Figure 13-1 Details of the CRM machine

The automated operation of the various key stages of crossing restoration have been developed and demonstrated within the In2Track3 project.

The challenges faced include the complex matrix of crossings and their different material types found in a railway network as shown in Table 13-1.

Table 13-1 Challenges of different crossing material types

Crossing Design & Materials				
Database		Material of Crossing Nose	Number (%) in NR network	Material of Wing Rail
Cast Centre Block		Predominantly AMS	12,012 (55.9)	Predominantly AMS
Cast Monobloc				
Part Fabricated	(cast vee)		1155 (5.4)	R220/R260/R350HT/HP335
Part Fabricated	(semi welded)	R260	1295 (6.0)	R260
Fabricated		R220/R260	5485 (25.5)	R220/R260/R350HT/HP335
Part Fabricated	(machined nose block)	Various alloy steels	403 (1.9)	R220/R260/R350HT/HP335
Others/blanks			1135 (5.3)	
		Total	21485	

Required CRM capability:

- 68 different crossing angles although 11 angles account for ≈80% of crossings (17,215 out of 21,485 crossings)
- 6 different crossing designs
- 3 material compositions (austenitic, pearlitic, alloyed steels) requiring distictly different approach to restoration

The challenge of controlling the weld deposit temperature, essential for restoration of cast manganese crossings, has been overcome through use of air knives following the welding gun and judicious development of the deposit weave pattern. The controlled heat input required for restoration of fabricated crossings has been facilitated through the incorporation of an induction heating probe ahead of the welding gun. These techniques require further optimisation to ensure required weld integrity.

The system is capable of automatically establishing the crossing angle by scanning the crossing nose. The scan data is used to precisely position the milling head to excavate the nose to the selected length, position the welding gun and undertake the required restoration. The milling cutter is then used to reform the required crossing nose profile.

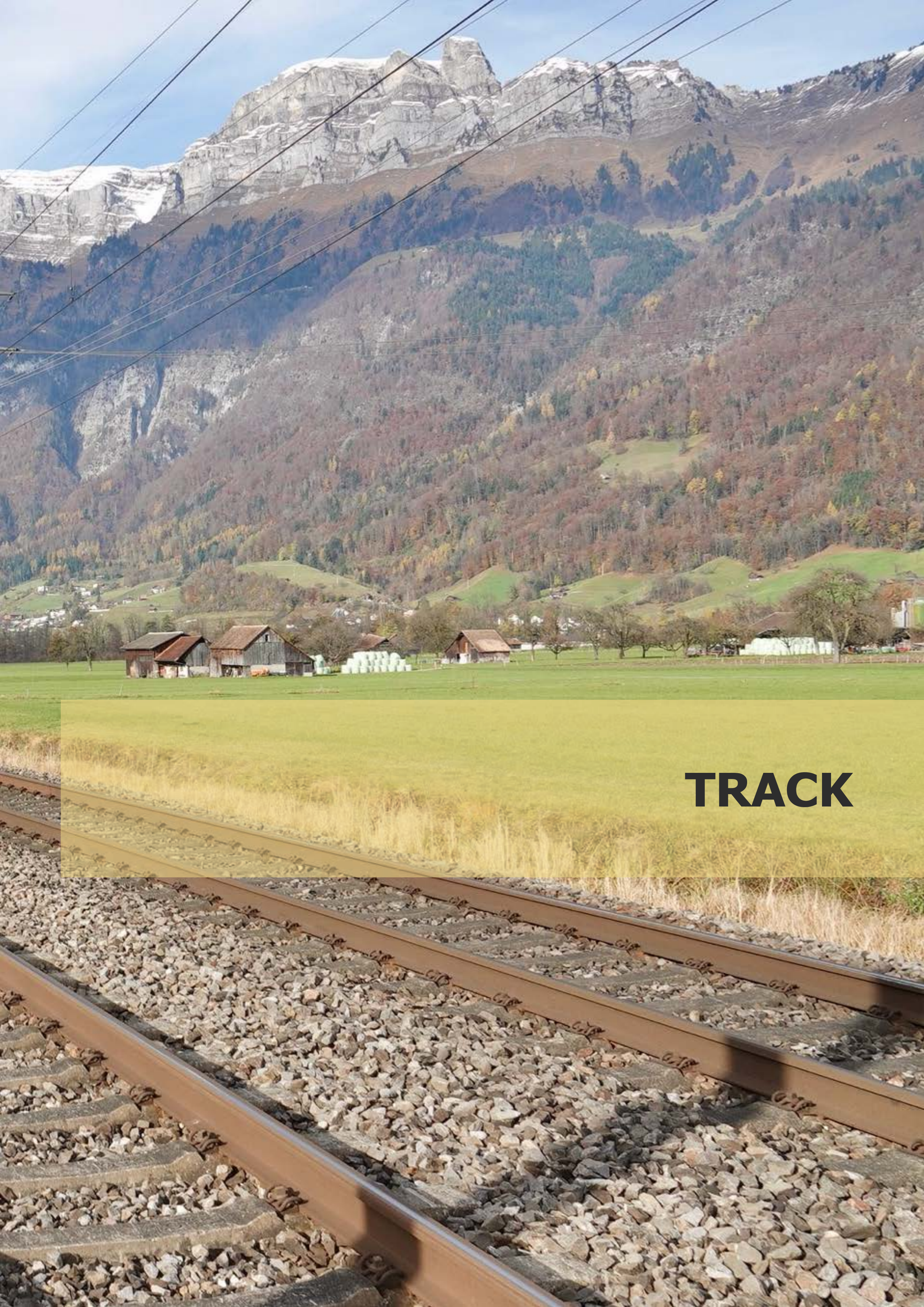
The repair process has the potential to be developed to enable additively manufactured crossing nose to be produced.

Implementation and open questions

The following next steps are proposed for development of the CRM:

- Establish, using dynamic simulations, suitability of proposed methodology of optimised nose corner and top profile for all crossing angles.
- Collation and combination of process control software developed for individual process stages to permit demonstration of restoration of full crossing layout.
- Process trials to optimise multi-layer deposition for restoration of cast AMS crossings and optimise process parameters for use of induction probe in front of welding gun for multi-layer deposition to restore fabricated / semi-welded crossings.
- Establish compliance with lower sector infrastructure gauge.
- Adapt machine guarding and on/off tracking system.
- Take the CRM unit and developed process through Product Acceptance procedures.

Deliverable(s): D2.6



TRACK

14 Higher precision requirements for slab track structures

Emil Aggestam, Jens Nielsen, *Chalmers University of Technology / Trafikverket*

Background

Modern railway tracks for high-speed traffic are often built based on a slab track design. With this design, where the concrete sleepers are replaced or combined with concrete plates, a more robust structure is obtained which offers higher availability and requires less maintenance. However, there are also major disadvantages of slab track compared to conventional ballasted track including higher construction cost and a larger environmental footprint due to the significant amount of concrete required.

General and specific requirements for slab track systems are given in the standard EN 16432-2. In EN 16432-2, dynamic vehicle loads are accounted for by applying a dynamic amplification factor that is independent of train speed and the level of track irregularities. For a given traffic scenario, it is difficult to develop an optimal slab track design with such a simple model. Thus, there is a need for a more detailed approach for the specification of the next-generation of slab track solutions. This specification should strike a balance between the robustness of the slab track structure and the costs and environmental consequences of an overdesigned solution.

Increased knowledge and implementable results

In this work, demands and procedures for evaluation of slab track structures have been developed in terms of structural integrity and robustness, life cycle cost and environmental footprint. The evaluation of structural robustness of slab tracks has been extended by calculating critical track responses for load cases not considered in EN 16432-2. Based on demonstration examples, it is argued that the current standard may lead to overly conservative designs inducing higher life cycle cost and environmental footprint than necessary. The conflict of interest between structural integrity and robustness, LCC and environmental footprint is discussed, and suggestions for how to optimise slab track structures are proposed.

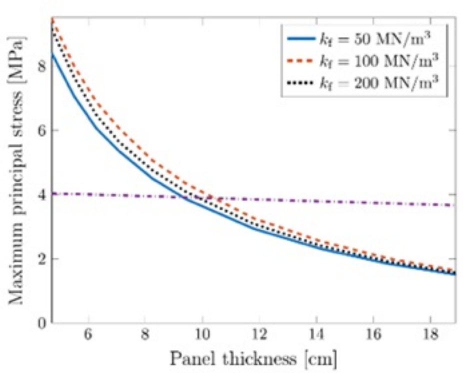


Figure 14-1 Maximum principal stress in concrete panel as a function of panel thickness for three foundation stiffnesses (bed moduli). The straight line indicates mean flexural tensile strength

To demonstrate the possibility to reduce the environmental footprint, figure 14-1 shows the maximum calculated principal stress in the concrete panel as a function of the thickness of the concrete panel for three different foundation stiffnesses. The simulations included vertical track irregularities which can be considered as a worst-case scenario for a high-speed line. By comparing the maximum principal stress of the concrete panel with the corresponding mean flexural tensile strength, it can be observed that the concrete panel would only crack if the thickness was smaller than or equal to 10 cm. Interestingly, based on EN 16432-2, the corresponding thickness would be 19 cm.

As an example of results from a novel load case, figure 14-2(a) shows the simulated distribution of the maximum bending moment that causes stresses in the longitudinal direction of the prefabricated slab element due to a 5.2 m long washout of the support. For comparison, the contribution of the dead weight of the superstructure to the distribution of maximum bending moment has been calculated, see figure 14-2(b). The load case is novel since variation in support conditions is not considered in EN 16432-2.

Furthermore, a model of reinforced concrete has been developed to predict crack widths, the bending stiffness of a cracked panel section and to assess whether the amount of steel reinforcement can be reduced. The model has been used to compare three different slab track designs to a ballasted track. For the investigated load cases involving representative wheel and track irregularities, it is concluded that the maximum stress in the concrete parts is, for all designs, below the maximum flexural tensile strength. Guidelines on how to assess innovative slab track designs have been presented, and extensions of the standard in terms of life cycle cost and environmental impact have been suggested.

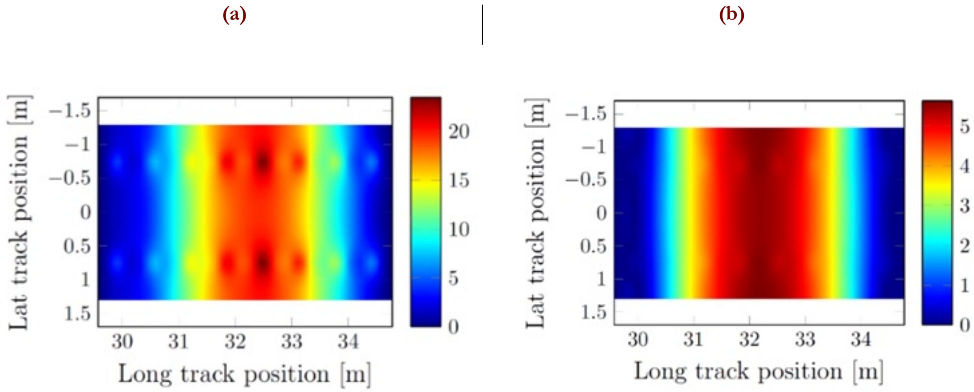


Figure 14-2 Distribution of maximum bending moment [kNm] leading to longitudinal stresses in the concrete panel: (a) dynamic vehicle load, (b) dead weight of the track superstructure. Both responses calculated for a 5.2 m washout below the centre of the panel

Implementation and open questions

The requirements presented in this work can be implemented in a revised European standard for slab track design. In particular, the work conducted here outlines how it can be revised by accounting for the effects of life cycle cost and environmental impact including the conflict of interest between these quantities and the structural integrity and robustness. In addition, further suggestions for improvements are given in terms of the evaluation of structural integrity and robustness. By applying representative wheel loads from simulations of dynamic vehicle–track interaction, and calculating the dynamic response of the track, higher precision requirements for slab track structures can be achieved compared to the traditional approach where a static calculation procedure with a dynamic amplification factor is applied.

Deliverable(s): D3.3

15 Reduced environmental footprint

Norbert Frank, *voestalpine Rail Technology*

Background

Sustainable management decisions include technical, economic, ecological, and social aspects. The basis for any assessment of innovations in rail infrastructure is the performance under operational track conditions. Besides more established methods in the rail sector like RAMS (Reliability, Availability, Maintenance and Safety) and LCC (Life Cycle Costs), LCA (Life Cycle Assessment) is gaining more and more importance on the environmental side for product development and for purchasing decisions.

The LCA is based on the standards ISO 14040 and ISO 14044. To allow reliable prediction of a product's environmental impact and prevent shifts between phases, all stages from raw material procurement to end of service life are taken into consideration.

Environmental Product Declarations (EPD) based on ISO 14025 and EN15804 are increasingly relevant as externally verified and standardised documents to evaluate environmental impact of products and facilitate comparisons. The EPD presents the Global Warming Potential in tons of CO2 equivalent per ton of rail steel as the main figure used for any assessment. It includes various environmental impacts like emissions to air, soil, and water; use of (fossil) energy sources; waste generation and handling. It is however limited to the production of the railway infrastructure component until the exit door of the manufacturing facility.

The aim of this work was to provide a quantification of the environmental effects, based on Life Cycle Assessment, which combines RAMS and LCC with their environmental impact. LCA should be performed for the whole life cycle to allow comparisons of different steel grades.

Increased knowledge and implementable results

An evaluation of two different rail grades was done by LCA assessment to evaluate the impact of different product lifespans on the environmental impact generated by rails. The calculations were extended from the EPD to include transportation, installation, and maintenance along the entire life cycle.

The example used track test results for R400HT and R260 rail steels in a curve of 300 m radius at high wear rates of a typical European mixed traffic track. It was shown that increased service life (from 2,3 years for R260 up to more than 14 years for R400HT rail steel) leads to a significant reduction of environmental impact and the corresponding carbon footprint by approximately 80 %, owing to less replacements needed for the R400HT rails.

The average annual CO2 equivalent for the respective rail steel is calculated by dividing the CO2-equivalent by the service life of the rail. This simple calculation method shows that the average annual CO2-equivalent for 1 km of R260 track is about 137 tonnes/year and 22 tonnes/year for R400HT. Thus, the average annual CO2-equivalent per km track can be reduced by 83 % for the selected curve by choosing the high strength R400HT steel grade.

Using the above methodology, whole railway lines can be analysed based on Open Street Map Data. The entire line is divided into segments of tangents and curves. For each curve, the radius and length of the segment is determined from the geographic data. Each segment is analysed individually for the theoretic life cycle, the cost KPIs and the CO2-equivalent. The whole LCA assessment is programmed in a Life Cycle Analysis Tool software tool (VAS LCC 2021) to handle the track analysis, the life cycle determination and deriving the CO2 equivalent. Input data are the track load, the radius and the selected rail type.

Two scenarios of application of a high strength rail steel grade 400UHC® HSH® (R400HT) and standard carbon grade R260 were compared for the Semmering area of Austrian Railways ÖBB to demonstrate the impact of the harder rail steel:

- The entire track is equipped with the R260 rail steel, independent of the curvature
- R400HT rail steel is used in curves with radii less than 3000 m, R260 in all other areas

The average annual CO2-equivalent is calculated for each individual curve separately and finally summed up for all segments of the entire 250 km of track. The results for the CO2 equivalents of these two scenarios show a reduction of the CO2-equivalent of 56 % by using the strategy with R400HT in curves below 3000 m radius:

- Benchmark Strategy – R260 only: 7.300 to CO2 / year
- LCC-optimised strategy – R400HT in curves: 4.100 to CO2 / year

In addition, another example considers the demonstrators of the new rail steel 340 Dobain® HSH®. It has a non-pearlitic steel microstructure, aiming to be free of head checks.

For the present work, the studied track part has a curve radius of nearly 1000 m, 1.14 km track length and annually 10 MBGT mixed traffic. The main damage mode is head-checking, requiring machining (grinding, milling) of the rail head profile to remove the damaged surface layer. The result of the annual Global Warming Potential shows a reduction of approx. 43% CO2-eq/km and year for the new 340 Dobain® HSH® compared to the R260 rail steel (Table 15.1).

Table 15-1 CO2-eq contributions in detail

CO2 eq-tons	R260	340 Dobain® HSH®	saving
production	19,25	11,11	42,3%
transport	0,75	0,61	19,2%
maintenance/installation	1,00	0,20	79,9%
total	21,00	11,91	43,3%

Main and far the largest contribution is still the manufacture of rail, where the CO2 emissions per year of use of the new 340 Dobain® HSH® are low due to the longer service life.

Implementation and open questions

The developed methodology is a profound instrument to determine ecological impact for new track installations and re-railing, and allows to choose the most sustainable rail steel strategy

By significantly extending service lives and reducing maintenance requirements at the same time, rail steels with better track performance not only result in improved LCC and RAMS figures, but considerably affect the carbon footprint of rails in a very effective way.

Deliverable(s): D3.3

16 Design of transition zones

Jens Nielsen, Kourosh Nasrollahi, *Chalmers University of Technology / Trafikverket*

Background

In a transition zone (TZ) between two different track forms, there is a discontinuity in the track structure leading to a gradient in track stiffness. Examples include transitions between different superstructures, e.g., slab track to ballasted track, and/or between different substructures, e.g., embankment to a bridge or tunnel structure. Differences in loading and support conditions at the interfaces between the track superstructure and the substructure on either side of the transition may lead to differential track settlement and an irregularity in longitudinal rail level soon after construction. This results in an amplification of the dynamic traffic loading along the transition, contributing to the degradation process of ballast and subgrade and a further deterioration of the vertical track geometry. Thus, track adjacent to a transition is prone to deteriorate at an accelerating rate, and frequent maintenance work may be required. To ensure the safety of railway operations and reduce life cycle costs, it is necessary to monitor the condition of TZs to detect operational changes at an early stage.

Increased knowledge and implementable results

A simulation procedure has been developed for the prediction of differential track settlement using a two-dimensional (2D) model of a TZ between slab track and ballasted track, see figure 16-1(a). It is based on an iterative approach where a time-domain model of vertical dynamic vehicle–track interaction in the short term is integrated with a model of accumulated ballast/subgrade settlement in the long term. The calculated load maxima at the interface between each sleeper and ballast in the ballasted track section, generated by the combined action from the gravity load on the track structure and the loading from each of the wheels of the vehicle model, are used as input to an empirical settlement model. The short-term model of track dynamics is updated in each iteration step to account for the new conditions of each sleeper support. By taking several iteration steps, the accumulated long-term differential settlement, the development of voided sleepers, and the resulting redistribution of foundation loads between adjacent sleepers can be predicted.

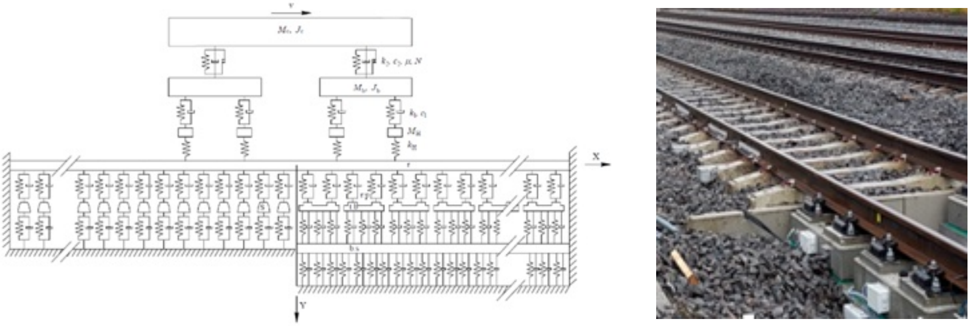
The simulation procedure has been demonstrated by calculating the differential settlement in the TZ between a ballasted track and a 3MB slab track due to an accumulated traffic load corresponding to three years of traffic. The model was aimed to mimic the conditions in the In2Track3 field demonstrator at Gransjö on Malmbanan. Under sleeper pads to smooth the stiffness gradient were considered. The individual effects of stiffness gradient and misalignment in rail level due to consolidation of the ballast layer soon after construction have been evaluated. It was found that the contribution from the stiffness gradient to the dynamic loading of the TZ was smaller than the contribution from the studied track misalignment. As often observed in the field, a dip in longitudinal level evolved on the ballasted side adjacent to the transition. The uniform settlement of the ballasted track and the magnitude of the track irregularity at the transition increased with increasing axle load.

Based on pre-test planning using the simulation model, a fibre Bragg grating-based setup for long-term condition monitoring of track bed degradation in the TZ at Gransjö was developed and implemented to provide data for verification and calibration of the simulation model, see figure 16-1(b). The instrumentation along the transition included four clusters, each with an optical strain gauge array on the rail web in one sleeper bay, and an accelerometer and a displacement transducer on the sleeper. The settlement of several sleepers and the first block on the slab side were also measured on several occasions using a total station. Condition monitoring of the TZ commenced immediately after the track construction in September 2022 and continued until June 2023.

An example of the measured long-term settlement of two sleepers 5 and 11 numbered from slab track in the TZ is shown in figure 16-2. It was concluded that the implemented displacement and strain sensors were able to effectively capture the overall dynamic range of the system, indicating that the collected data can accurately represent the dynamic response of the TZ and be applied for the calibration of the simulation model.

Implementation and open questions

The 2D simulation model will be extended by implementing a layer of discrete ballast masses below the sleepers and a shear coupling between each pair of adjacent ballast masses. The aim is to consider sleeper interaction through the ground, while avoiding the large additional computational cost of a full 3D model of the TZ. Once the simulation model has been verified versus the measurements at Gransjö, the development of TZ design between slab track and ballasted track using various measures to control the stiffness gradient and reduce the loads on the supporting ballast can be evaluated before implementation in the field.



(a) (b)

Figure 16-1 (a) Sketch of 2D vehicle and track models (x < 0: ballasted track, x > 0: slab track). (b) Overview of instrumented TZ between ballasted track and 3MB slab track at Gransjö, north of Boden in Sweden

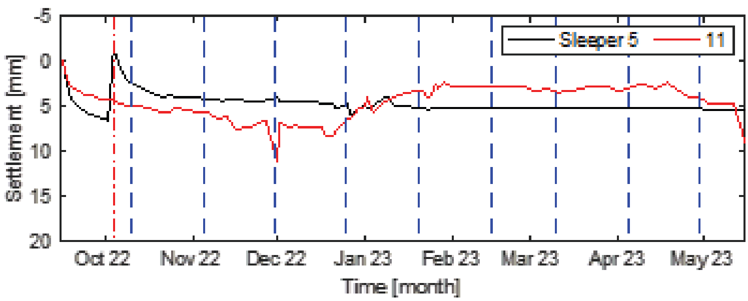


Figure 16-2 Evolution of unloaded sleeper displacement (settlement) over time for sleepers 5 and 11. Dashed vertical lines mark the accumulated traffic load, with each pair of lines representing 1 MGT

Deliverable(s): D3.3

17 Track status assessment

Anders Ekberg, Elena Kabo, *Chalmers University of Technology / Trafikverket*

Background

For a track infrastructure manager, the current track status and how it will evolve in the future are probably the two most important pieces of information required for operational management. To obtain this information requires knowledge of the different deterioration phenomena, their influencing parameters, and how these relate to available models to predict deterioration rates. An overview of this topic was presented in In2Track2, which also provided an overview of available monitoring and predictive abilities.

The study in In2Track3 expands that work by being more specific on possible prediction strategies with focus on rail and wheel health management strategies. This includes examples on how to perform overview calculations in some areas, which is key in the development of more sophisticated digital twins. Further, it is investigated how health management strategies relate to asset management system requirements in the ISO 55000 standards and to common safety methods for risk analyses (CSM-RA).

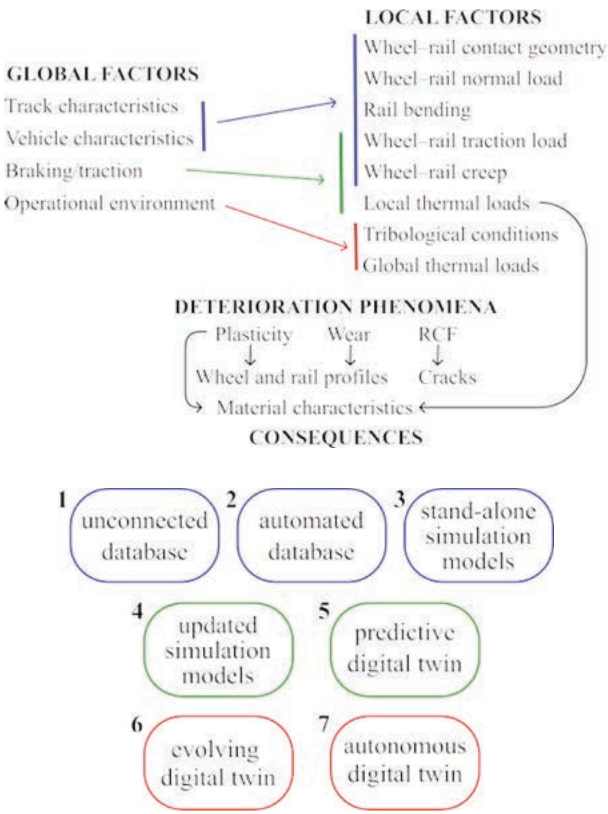


Figure 17-1 Top: Relations between some global operational conditions, local influencing factors, subsequent phenomena, and resulting consequences. Bottom: Evolution of "digital twins" from stand-alone databases and models (1–3), through models updated from measured data (4–5), to automatically updated digital twins (6–7)

Increased knowledge and implementable results

For several deterioration mechanisms (see figure 17-1 Top) means of status characterisation, and approaches to predict degradation have been charted. In addition to these overviews, wheel and rail health management strategies are investigated. In this context, the concept of digital twins plays a crucial role. A categorisation of different types of digital twins is proposed to clarify this often-misused concept (see figure 17-1 Bottom). The focus in the research has been on levels 5 and 6. It is shown how digital twins relate to time- (or load-) based maintenance scheduling (where degradation is presumed to be related only to time or load), to safety and maintenance limits (where the maintenance planning is complemented with an establishment of levels where failure risks are high), and to AI-based maintenance scheduling (where deterioration is typically predicted from historical data without any physical modelling). It is discussed when (and why) different approaches are applicable. In particular, AI and other data-driven approaches are ill-suited for identifying safety risks and to predict consequences of altered operational conditions since they consider a steady-state situation. In general, it is therefore recommended that a combination of physical modelling and data analysis should be employed where smaller, but better controlled simulations are used to establish maintenance and safety limits.

This leads to a discussion on asset management systems. The demands in the ISO 55000 series are scrutinised and related to the topic of track status and deterioration. The demands in standards on risk analyses, and some challenges related to such analyses are discussed. Here the importance of understanding deterioration characteristics is stressed: phenomena leading to rapid failures require safety limits on operational conditions, whereas more gradual phenomena can be handled by regular inspections.

Implementation and open questions

The investigation is published in a scientific journal paper to support further research and implementation.

For some deterioration phenomena e.g., wear and rail cracks, it is reasonably well established to which parameters (current and future) status should be related. Here, inspections and measurements are often performed to establish the status. It is however often not fully clear how this status should be quantified in relation to the measurable quantities. As an example, railhead wear is often characterised by a few profile measures that do not provide the full picture of how detrimental the worn profile is. In many cases, this is made even worse by the fact that available sensor/monitoring/inspection techniques are not functioning at their optimum in an operational railway context. As an example, crack detection devices are hindered by the damaged and/or anisotropic rail surface and the need for speedy inspections that limits the resolution that can be obtained. The situation typically leads to compromises between measurement accuracy and operational disturbances (in a broad sense). The research in In2Track3 is showing ways to bridge this gap by complementing measurements with numerical simulations and presents possibilities for both. This will support the further implementation in operations.

Deliverable(s): D3.4

18 Rail defect detection from axle box accelerations

Matti Rantatalo, *Trafikverket*

Background

Rail maintenance is one of the larger maintenance activities performed by an infra structure manager. The rail status can be assessed based on manual inspections or by measurement vehicles using for example axle box acceleration (ABA), eddy current sensors, or visual inspection methods. To increase the inspection intervals the usage of in-service trains in combination with the existing dedicated measurement vehicles could be a cost-effective alternative e.g., when looking for rail defects like squats or other surface defects.

The main advantage of using a locomotive installation for an ABA system, compared to a freight or passenger wagon installation, is the easy access to electrical power, cabinets for technical equipment and the fixed weight of the train, granting a higher degree of reproducibility. Sheltered environment and a steady power supply can also be found in passenger cars and in some freight wagons; however, in these vehicles, axel load might change during operation due to changing cargo loads. The main disadvantage with a locomotive installation is the added disturbances caused by traction motors and drivelines. This study aims to investigate if the vibration-based approach can be used when accelerometers are installed on the motor and drive train block of a motorised wheelset, Instead of on a axle box of a traditional clean wheelset.

The main related issues are how an ABA system would perform on an in-service freight locomotive and what initial steps that have to be taken when converting the ABA detection signal into information suitable for determining needs for rail grinding.

Increased knowledge and implementable results

In figure 18-1 an example of an in-service train measurement can be seen. The upper graphs show the raw ABA acceleration signal obtained by the system. The lower graph shows the identified peak anomalies that could originate from point defects along the rail. By analysing all measurements, it was evident that the measurements included a slightly different set of peaks. Some measurements had additional indications of impacts compared to others. This could be due to disturbance from the motors drive train arrangement and was in some way expected. To overcome this, an approach using the cumulative sum of detected peaks over the line section was applied, see figure 18-2. In this figure the left graph shows a scatterplot in the coordinate (long, lat) system (Latitude and Longitude). The middle graph shows an intensity plot projected on the Latitude coordinate. The right graph shows the cumulative sum of the detected peak intensity over the Latitude coordinate.

By examining the cumulative sum, a large increasing step in the cumulative intensity represents a higher probability that that location is associated with a defect or with an impact generated component like a bad insulation joint. The steps in the cumulative graph were localised by their centre point coordinate and the intensity of the step (height of the step) was used as the level of severity of the detected impact. By comparing the result with the verified results provided by walking inspection of the area it could be concluded that the cumulative approach could neutralise the disturbances which could have its origin in motor and drive train disturbances.

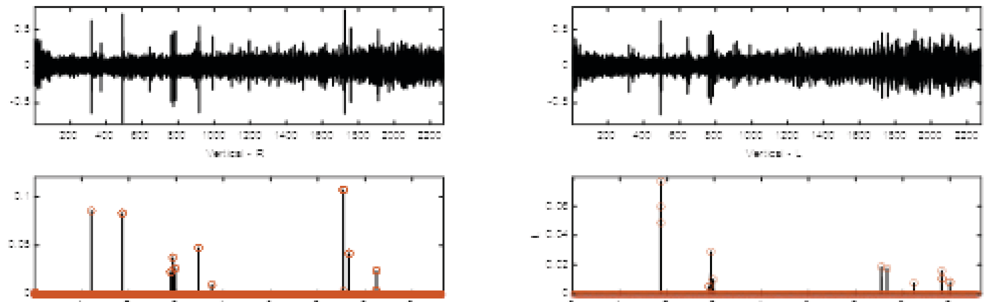


Figure 18-1 Example of a ABA measurement result. Upper graphs shows the raw acceleration signal with (y-axis in [g] and x-axis in meters). Lower graphs shows the detected anomalies for both rails (y-axis in relative intensity, x-axis in meters)

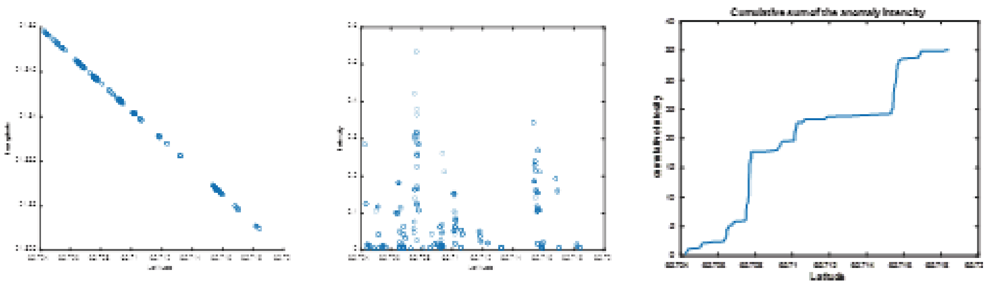


Figure 18-2 Detected peaks along the measurement section. Left graph shows a scatterplot in the coordinate system. The middle graph shows an intensity plot projected on the Latitude coordinate. Right graph shows the cumulative sum of the detected peak intensity over the Latitude coordinate

Implementation and open questions

Based on the result it is evident that a single ABA measurement from an in-service train can include detections that are not related to any rail defects. To overcome this an average of many different measurements must be used. This study proposes a process where ABA measurement results will be combined by using the cumulative sum of the peak/impact intensity. The process should then include a step where additional measurement/inspection systems should be added, like image processing, to label the different types of peak/impacts, e.g., separating insulation joints and welds from rail defects. The labelled data can then be used to train a machine learning algorithm which can feed a rail grinding decision process.

Deliverable(s): D3.4

19 Assessment of renovation critical areas

Amine Dhemaied, *SNCF Réseau*

Background

Ballast and track regeneration processes for SNCF Réseau ballasted tracks are initiated by track regeneration master plans, followed by track investigations, track studies and finally ballast/track regeneration works. However, the lack of a thorough track system analysis, including substructure, constitutes a drawback in these processes. Track maintenance teams do not have information on track bed health status. Therefore, track bed failures are neglected in track maintenance assessments and works.

In some cases, ballast and track regeneration appears to be insufficient to recover track anomalies. Track disorders can be related to several causes, such as bad mechanical properties of the railway embankment, layer saturation or other environmental issues. An analysis of the whole system can therefore help to identify the origins of the observed problems and to propose an efficient and adapted track regeneration work.

To overcome this absence of thorough track system analysis, an improved system-wide process for track regeneration decision-making, along with an associated decision tool needs to be created. This tool would provide a global view of track bed health status to support decisions for long term track performance. This would lead to a global decrease in track maintenance cost and an increase in track availability.

Increased knowledge and implementable results

This project showed us that we had to take into account several factors combined, such as track geometry over the last 10 years, track maintenance work over the last 10 years, environmental parameters of the embankment (including results from Ground Penetrating Radar, dynamic penetrometer tests, coring, drainage diagnostics, rainfall statistics etc.) and external environmental parameters (geological situation, or rising groundwater risk etc.), to provide an indicator that reflects the state of health of the track system for each track zone. Further, visualisation of the parameters is used to determine the rating.

Thanks to this in-depth diagnostic tool, asset managers and track regeneration planning teams will be able to propose optimal and appropriate technical solutions for regeneration.

We understood that, to prioritise the areas to be maintained, three criteria could be taken into account:

- the environmental risk index of the track, which considers the embankment environmental parameters (Ground Penetrating Radar, drainage diagnosis as well as external parameters including geological situation, rising groundwater risk, risk related to heavy rainfall, etc.).
- the number of manual maintenance works (RL) over 10 years.
- the number of mechanical maintenance works (BML) over 10 years.

Decision rules are then used to assign each track section to a priority level according to these criteria described below. A first version of the diagnostic tool has been developed. It allows to visualise:

- the criteria mentioned above as well as the priority given for each parameters of the studied track.
- the track geometry data associated to each track section to have an overview of the data available for each track section.

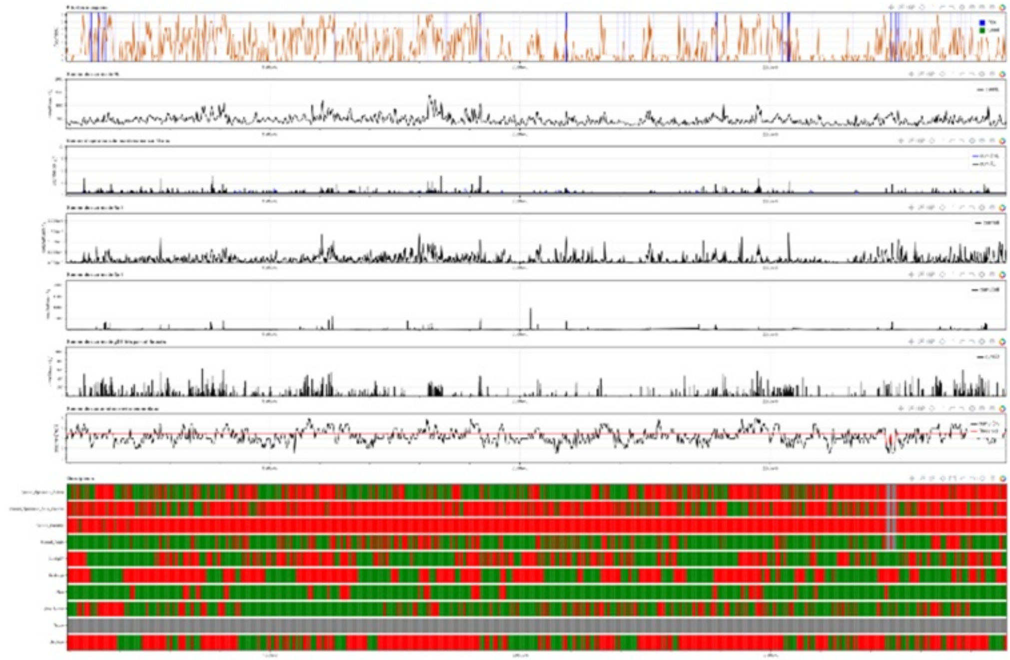


Figure 19-1 Example of visualisation allowed by the diagnostic tool

Implementation and open questions

The improved process and decision tool for track system regeneration will be implemented at a large scale on an existing ballasted high-speed line, which is planned to be regenerated in the coming years.

There is also work in progress to integrate this diagnostic tool to an SNCF multi-trade application, based on IRISSYS software, which enables knowledge of the state of the network and projections of its evolution regarding status of track, rail, platforms etc.

The integration of the diagnostic tool in that application will allow, among other things, to add the track geometry data mentioned above to the diagnostic tool.

Deliverable(s): D3.4

20 Development of autonomous rail defect inspection

Feiyang He, Isidro Durazo Cardenas, Andrew Starr, *Cranfield University / Network Rail*

Background

Railway transports are steadily recovering from the coronavirus (COVID-19) pandemic. UK's rail factsheet: 2022 shows 990 million passenger rail journeys were made and 6.87 billion net tonne kilometres of rail freight were transported in 2022, an increase of 155.2% and 11.3%, respectively, on the previous year. The increased rail transport demands have put considerable pressure on the existing tracks. As a result, the rail industry faces a significant challenge in inspection, maintenance, and improving track reliability.

Nowadays, track inspections can be undertaken through a combination of:

- Inspection using specialist track inspection vehicles
- On-foot inspections
- Service train inspections

Nevertheless, they all require some level of intervention by a human worker. Labour-intensive operations significantly raise safety risk concerns and inspection costs. UK's Rail staff suffered 83 specified injuries on all rail networks from 2022 to 2023 based on the Rail Safety report from the Office of Rail and Road, UK. Therefore, safety concerns were the primary change drivers in developing new inspection techniques. No rail workers will be injured if we introduce an autonomous rail inspection system.

Furthermore, Annual Efficiency and Financial Assessment (AEFA) from Network Rail (NR) has reported that they spent £2,089 million maintaining the condition and capability of the existing infrastructure to the previously assessed standard of performance from April 2022 to March 2023, underperforming by £214 million. This underperformance can be attributed to dealing with staffing disruption and compliance with internal safety standards. Thus, the project proposed the autonomous rail inspection system to reduce pedestrian inspections, which can mitigate financial issues.

Increased knowledge and implementable results

Figure 20-1 Autonomous rail inspection trolley

This project successfully demonstrated and validated the feasibility of autonomous rail inspections up to Technology Readiness Level (TRL) 7.

As shown in figure 20-1, a prototype was constructed by integrating an autonomous rail vehicle and an Ultrasound Testing (UT) system from Sperry.

As depicted in figure 20-2, a system's use case was drafted. Two demonstrations were conducted to test the prototype under TRL 5 and 7 environments.

An initial TRL 5 test was conducted at the Rail and Innovation Test Area (RITA), Cranfield University, UK. GPS localisation error was found to be approximately 1.9 metres.

A final demonstration at TRL7 was conducted using the Ecclesbourne Valley Railway at Idridgehay, Derbyshire, UK. The process was executed accurately in nine test rounds, validating the feasibility of the autonomous rail inspection system in a TRL7-required environment.

The odometry error ranges from -1.45 to 3.2 meters. The source was attributed to wheel slippage during operation.

The collected data were analysed using Sperry's online AI tool, Elmer®.

28 of 32 total artificial defects were correctly identified on the tracks.

Implementation and open questions

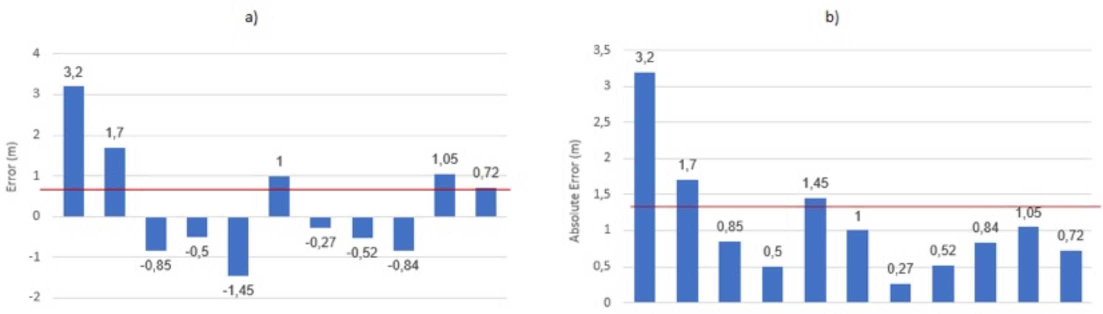


Figure 20-2 Measured error of each test

Progress is still required for the final commercialisation and deployment. The project found some challenges and limitations during the demonstrations, which should be addressed in future iterations, including:

- The overall system's localisation accuracy was limited due to the current configuration, which lacked differential GPS and a fused approach for GPS, IMU and odometry. A potential solution is to apply differential GPS and sensor fusion to improve positioning performance.
- The system provides a preliminary indication of the defect size but not an exact measurement. Ongoing development of automatic defect sizing technology with advanced algorithms and comprehensive data sets for improved accuracy is required.
- During the tests, the communication signal strength was extremely weak, adversely affecting the operator-prototype communication and the Sperry system's data-uploading procedure.

Deliverable(s): D4.2

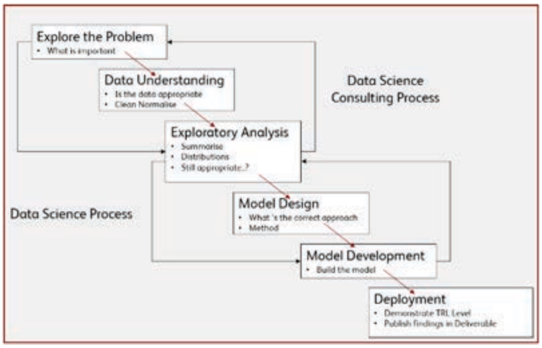
21 Data mining to identify performance critical parameters

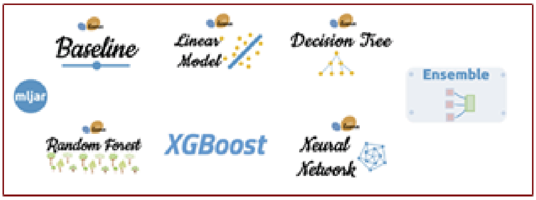
Ian Dean, *Network Rail*

Background

Track geometry management is crucial for railway safety, with European railways using monitoring trains to measure track geometry. Safety and maintenance limit values help prevent and intervene when infrastructure is in trouble. This project explores using Artificial Intelligence and Machine Learning to develop accurate models of degradation, incorporating additional infrastructure and weather data sets to improve prediction accuracy. The project examined two different routes out of London on the UK network that had different degradation behaviours, one near linear, the other nonlinear.

Increased knowledge and implementable results



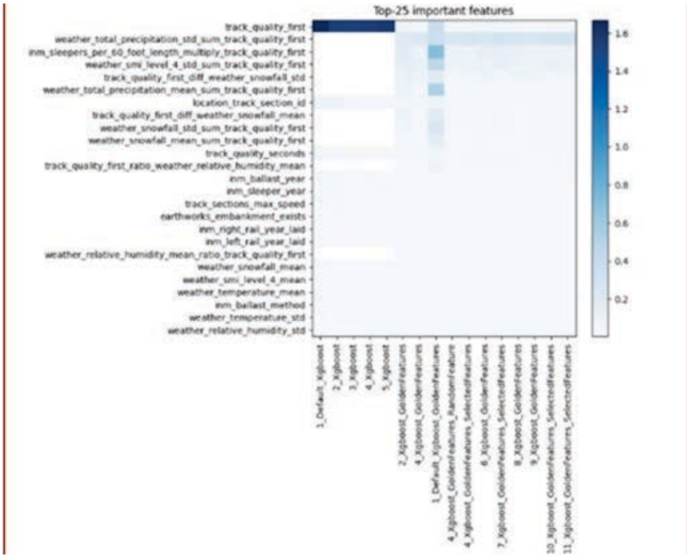


The project discovered that a Data Science Project involves significant work in preparing, aligning, cleaning, and transforming data sources. Once machine-readable, iterative processes are needed to identify key data features for a robust model, various AI and ML techniques can be used, balancing computational efficiency and model accuracy.

Specific to this project, improved track geometry prediction can be achieved and the best performing algorithm utilising AUTO ML JAR, was Xtreme Gradient Boost Regressor. This approach is a scalable, distributed gradient-boosted decision tree machine learning library. Gradient boosting is the term used where a single weak model is combined with other weak models to generate a collectively stronger model where targeted outcomes of each case are based on the gradient of the error.

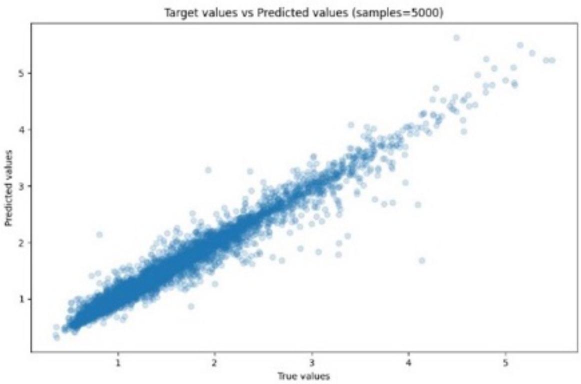
The result of this project yields that AI & ML techniques do have practical applications in identifying critical performance parameters, as ranked in the adjacent figure.

These can contribute towards predictive models so that Infrastructure Manager can undertake more effective maintenance planning reducing service affecting failures with a models of a confidence level measured with a coefficient of determination of 0.956.



Implementation and open questions

This approach can be scaled up to encompass larger geographic areas and more historic data. Utilizing higher volumes of data types such as soil types, weather, track componentry age, and traffic data, improves results but trades machine training time. Higher-performing hardware and cloud computing technologies may offset this trade-off. Presently, an engineer's standard laptop PC is proven capable to machine learn 630km of track, over 2 years of related infrastructure and weather-related data, in under 26 minutes and produce an optimum model that has a coefficient of determination of 0.955 and a root mean square error of 0.16mm for a standard deviation of longitudinal level over each 200m section.



This project also established the significant human effort in preparing existing data sets for machine learning. Should Infrastructure Managers wish to exploit this technology, their data preparation strategy will require revision so that normal operational data gathering is automated to produce machine readable training data to annually update models.

A nationally scaled up application that predicts track quality, enables proactive maintenance intervention planning and timely delivery of on track machine volumes. This helps save operational expenditure, reduce service failures, and potentially informs strategic decision-making on capital expenditure.

Deliverable(s): D3.4

22 Detection of rail level defects using the Electro-Magnetic Acoustic Transducer method

Valentin Vlieghe, Quentin Mayolle, Denovan Lampin, *IRT Railenium*

Background

The efficient and safe functioning of rail transportation systems is vital for the smooth movement of goods and passengers. However, one of the significant challenges faced by railway operators worldwide is the occurrence of rail defects. These defects, ranging from minor irregularities to severe structural issues, pose a serious threat to the integrity and reliability of rail infrastructure. Rail defects not only jeopardise the safety of train operations but also lead to increased maintenance costs and potential disruptions in the overall railway network. The main requirement is therefore to detect and model the evolution of a defect inside the rail to optimise maintenance plans.

In response to these challenges, adaptations on rail applications of non-destructive testing technologies have emerged, with Electro-Magnetic Acoustic Transducer (EMAT) sensors gaining prominence. EMAT sensors use electromagnetic fields to generate and receive ultrasonic waves within the rail material without direct contact. EMAT sensors offer several advantages over traditional methods. Their non-contact nature reduces the need for extensive rail preparation. They can detect both surface and subsurface defects, providing a comprehensive assessment of rail integrity. Their suitability for online inspections ensures timely assessments without disrupting regular operations.

This study focuses on evaluating EMAT technology for surface defects detection and analysing its feasibility for implementation. The integration of cutting-edge technologies like EMAT holds promise for the proactive identification and management of surface defects, ensuring the ongoing efficiency and safety of rail transportation systems. Embracing such innovations reflects a commitment to advancing railway safety and reliability in the face of evolving challenges.

Increased knowledge and implementable results

Figure 22-1 EMAT trolley

Analysing rail surface defects necessitates data acquisition. To fulfil this requirement, a trolley has been designed and fabricated, incorporating considerations for employing EMAT sensors. This trolley enables the acquisition of ultrasonic measurements on rails in the field. In addition to the mechanical components, two software applications have been developed for trolley control and data acquisition. These programs have undergone testing and validation to align with our specific requirements.

Consequently, two measurement campaigns were conducted, during which the position of EMAT sensors was monitored for signal optimisation. Signal processing is imperative for analysing in-field data, and during these measurement campaigns, the detection of rail defects was successfully validated.

To cope with in-field external perturbations, which disturb the data acquisition process, a development of advanced signal processing algorithm has been performed. Important levels of noises (electrical or from mechanical vibrations) are alleviated with powerful time-frequency representation of EMAT measurements. Algorithms based on Superlets (improved version of Wavelets) estimate the Time of Flight of the ultrasonic wave in low Signal to Noise Ratio situations. Simulations were made to demonstrate the benefits of the methodology, in comparison to classical approaches. Its implementation on the trolley software allows a direct use during online experiments without hindering the performance of the analysis.

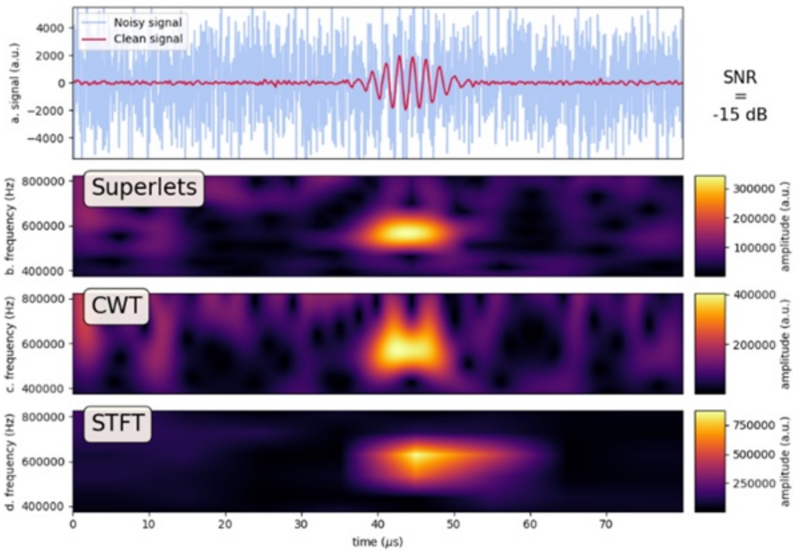


Figure 22-2 Comparison of time-frequency representations: Short Term Fourier Transform (STFT, bottom), Continuous Wavelet Transform (CWT, middle) and Superlets (top)

Implementation and open questions

An important oncoming improvement of the inspection trolley is the mixed use of sensors of different natures. To cover the whole range of defects (internal, surface or foot defect), different technologies are required: ultrasonic sensors, Eddy Current sensors and EMAT sensors should perform their acquisition simultaneously on the rail. Mechanical adaptations would prevent disturbances between them, but advanced information fusion methodologies must be developed, using signals of heterogeneous characteristics.

Integration of EMAT into the rail industry would also require intensive testing of the system of real and aged rails, to ensure a complete detection of existing defects. Thousands of kilometres should be inspected with the trolley to estimate the in-field performance of the presented methodology. Possible mechanical evolution of the trolley are expected to take into account the versatility of the rail network.

Deliverable(s): D4.4

23 Embedded sensors for prognostics and health management

Asma Ladj, *IRT Railenium*

Background

Railways, showing significant growth in recent decades, hold a paramount position in the transportation sector. This fact has prompted infrastructure managers to focus on promoting service quality (trains punctuality, travel comfort) as well as avoidance of safety hazards. Tracks, as safety-critical and vital components in railway systems, require crucial attention to deploy reliable and cost-effective maintenance strategies, able to accurately detect and predict, as early as possible, any faults that may affect their operation. In this context, Prognostics and Health Management (PHM) offers promising opportunities for the design and implementation of effective predictive maintenance. Key technologies, enabling successful development of PHM in railway industry, include condition monitoring technologies, involving sensing and networking techniques, coupled with powerful methods for data processing leveraging artificial intelligence. The emergence of internet of things (IoT), supported by the proliferation of low-cost sensing solutions and the maturity of ICT (information and communication technologies), allows the deployment of condition monitoring systems (CMS), built based on connected and smart devices.

Today's challenges are around the eco-responsible development of CMS and the digitisation of infrastructures already in place. The objective of this project is to design complete embedded solution, for continuous and automated monitoring of the tracks and their environment, while dealing with railway application constraints and meeting requirements outlined by railway standards. To achieve this goal, modules capturing, transferring, and processing data should be carefully built. This involves hardware and software development, as well as mechanical integration of the sensor devices. Additionally, robust and efficient data processing techniques for track failure detection and prediction should be developed.

Increased knowledge and implementable results

The proposed CMS for track predictive maintenance integrates several sensors adapted for railway environment and able to monitor track temperature (thermal resistance), acceleration (accelerometers), noise (microphone), water level, and geolocation (GPS). The first version of the CMS embedded all sensors together in the same housing and implements all functionalities on the same electronic card. Despite this practical design, simple and easy to install and maintain, the major issue is measurements accuracy. Since measurements reliability is primordial to ensure an efficient decision making, the CMS is split into several independent sensor nodes (IoT devices), each acquiring a defined measurement and able to autonomously communicate the collected data. This new "plug and play" design offers a greater flexibility and makes the CMS able to cater to various types of measurements. Moreover, more reliable measurements are collected by using more robust mechanical integration methods, adapted to each sensor type (see Figure 23-1).

Figure 23-1 Examples of sensor node integration: (a) Acceleration sensor, (b) Temperature sensor, (c) Water level sensor

The collected data is transferred by each sensor node to a near gateway and then relayed to the remote server using LoRa (Long Range) or LTE (Long-Term Evolution) technology. This redundancy enables to deal with railway environment disturbance and the influence of weather conditions. Sensor nodes are self-powered (via internal batteries) or through a solar panel, installed near the track section and linked to the gateway.

The collected data is processed and presented to final users through a web application, where complete and intuitive dashboards are displayed. Action/reaction algorithms based on fixed thresholds are implemented on each sensor to immediately alert the user in the case of an abnormal situation. Moreover, AI (artificial intelligence) based model is used to detect and predict faulty events by processing track vibration data. This model requires low memory and computation capacity, to fit in IoT sensors microcontrollers, with restricted resources.

Implementation and open questions

A series of exhaustive lab tests are done to validate system functioning and assess its performance. The sensors were deployed on relevant environment and several environmental (autonomy, sealing, resistance, electromagnetic compatibility (EMC), Restriction of Hazardous Substances (RoHS), etc.) and functional (sleep mode, waking up, measurement, and communication) tests have been carried out. All these tests, addressing both environmental considerations and core functional capabilities, have been achieved successfully. To reach higher TRL (TRL6) and assess the robustness and effectiveness of the system under real conditions, the sensors and embedded PHM algorithms were installed in operational track, in collaboration with Infraestruturas de Portugal.

Although the system is operating effectively and data is being continuously collected from the monitored track section, additional time is required to acquire a more extensive dataset and achieve more comprehensive results. An initial phase is needed to build a reliable reference database and train AI-based algorithms for failure prediction. Indeed, the model performance highly depends on the quality of the training database. Moreover, it is important to iteratively refine and update the model as more data become available. Combining information from multiple sources using data fusion techniques would be a promising perspective, leveraging different sensors measurements to build a more effective prediction model.

Deliverable(s): D3.4

24 Track buckling

Elena Kabo, Anders Ekberg & Kalle Karttunen, *Chalmers University of Technology / Trafikverket*

Background

Track buckling is a phenomenon where the restricted thermal expansion of a rail induces high compressive forces that causes the track structure to buckle. This produces a very significant risk for derailments and requires corrective maintenance before traffic can commence. Matching the peak temperature of the year to the number of occurring track buckling events in Sweden (some 30 to 200 annually), it is found that track buckling does not relate to an "average" track, but to "weak" points along the track.

Track buckling is promoted by initial geometrical deviations in the track geometry and by a low resistance to lateral (and vertical) deflections of the track. The aim of the study in In2Track3 was to quantify the effect of local track conditions on the local buckling resistance of the track. This knowledge can be employed to identify track sections with the highest risk of buckling and quantify effects of maintenance actions. To this end, both numerical simulations, and statistical analyses of operational track buckling events are employed. To quantify the severity of different conditions an innovative concept of an equivalent temperature is developed.

Figure 24-1 Track buckle with corresponding evaluation of equivalent temperature as a sum of contributing factors. Picture Trafikverket.

Increased knowledge and implementable results

A numerical model to simulate track buckling was developed and used to quantify the influence of key track parameters on the track resistance by their equivalent temperature i.e., the temperature increase in the reference configuration that results in the same deflection as in the modified configuration. In other words, if a configuration corresponds to an equivalent temperature $\Delta T_{5.0}$ = 10°C, then a lateral displacement of 5 mm (in addition to the initial irregularity) will be obtained in the reference configuration if the temperature is 10°C higher than what gives a 5 mm lateral displacement in the modified configuration. Comparisons between the predicted influence and empirical ratings of the severity of different parameters generally show good agreement.

The influences of operational parameters difficult to include in the numerical simulations (e.g., track work and "fixed points" such as switches & crossings in the vicinity of the investigated track section) were then estimated through modifications of measured rail temperatures from track buckling reports to obtain an as narrow Gaussian distribution of track buckling temperatures as possible. Scrutinization of results from this statistical analysis combined with field experience from track experts indicated that the influence of "fixed points" is a minor issue for continuously welded tracks.

The identified equivalent temperatures for the influencing parameters were then employed to investigate track buckling events along a line. This study validated that the developed approach is operational and evaluates high equivalent temperatures (on the order of 50°C) at track buckling locations. It was also found that buckling is almost never related to a single cause. The case study has also revealed several remaining challenges. These include lack of, or faulty data in registers, insufficient precision in positioning, status assessment sensitive to personal judgement, and that the stress-free temperatures are often uncertain.

Implementation and open questions

The developed analysis models and the evaluation results are believed to be valuable tools in identifying track sections at risk of track buckling, and quantifying the effectiveness of different mitigating actions. The methodology of evaluating equivalent temperatures has been described in a scientific paper and has been shown to be operational in a case study. Challenges for a wide implementation in terms of improved register data and incident reporting have been highlighted.

In the study it was found that if many track buckling events occur on a line during one year, the number significantly decreases the following years. This indicates that the potential to prevent track buckling by maintenance efforts is high. Using the developed methodology, it will be possible to identify critical track sections with higher precision. This can be used to better target maintenance.

Deliverable(s): D3.3

25 Measurement of thermal rail stresses

Mike Poulter, *Network Rail*

Background

Thermal rail stress can become a safety critical factor in extreme weather conditions where the actual temperature is very different from the stress-free temperature (SFT). As the rail temperature rises above the SFT, the risk of track buckling increases. Speed restrictions and even line closures are used to mitigate the buckle risk in periods of the most extreme heat. Similarly, as the rail temperature drops below the SFT, the risk of rail failure increases as defects are placed under increased tension as the temperature drops. Climate change research forecasts significant increase in temperature variation that will result in a growth in rail buckle events and rail breaks unless additional mitigation is introduced. Installing and maintain the target SFT is important to minimise the combined risk from rail breaks and track buckles.

Railways generally set the SFT in their continuously welded rail above the average annual temperature to help to mitigate the risk of track buckling, in the UK the target SFT is 27°C. There are many factors that can modify the SFT over time including: rail wheel contact, track movement, any break and repair in the rail that is not properly restressed. Consequently, there are many areas of older track where the SFT is not known. Several different methods are used to measure SFT including cutting the rail and unclipping a length of track to measure the contraction and the VERSE method of unclipping a length of rail and elevating it to infer the stress. Methods are generally slow, expensive and lack accuracy.

The challenge for this project was to build on the In2Track2 assessment of ultrasonic methods to measure thermal stresses in rail, to develop an accurate, non-destructive, ultrasonic method of measuring SFT. Birefringence (Method A) and Universal (Method B) were considered.

Increased knowledge and implementable results

The initial laboratory testing failed to show the required accuracy for either method of ultrasonic stress measurement.

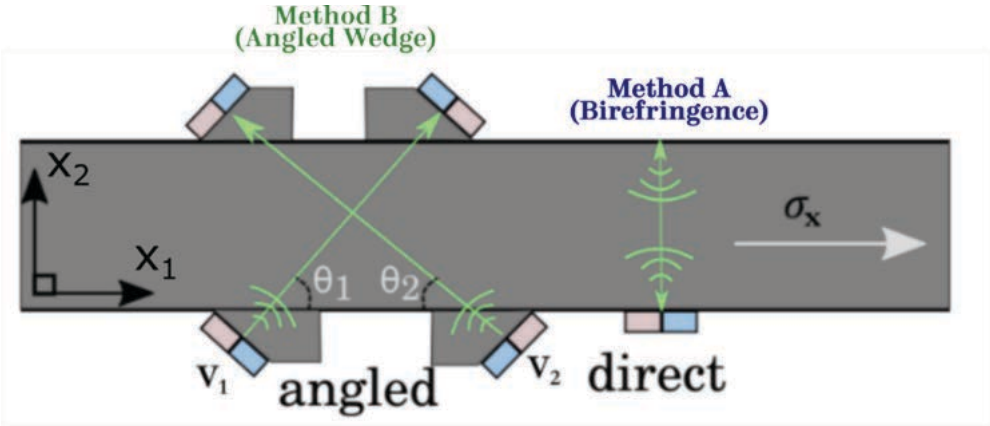
A theoretical sensitivity analysis considered the impact of minor changes to incidental variables including web thickness, surface roughness and sensor alignment. Method B showed extreme and unmanageable sensitivity to minor variations of these factors. The sensitivity of method A was still high but orders of magnitude lower than for method B and so this became the focus for development.

Further laboratory testing demonstrated that the planar waves average out variability in surface roughness or web thickness, such that control of these factors was achieved to an acceptable level under laboratory conditions. Requirements for the optimum sensor clamping force and couplant volume were defined.

Laboratory measurements revealed two main components contributing to method A's error: variation in unstressed speed of sound between the orthogonally polarised shear waves (zero-offset) and variation in measured acoustoelastic constants. A test procedure was developed to determine the birefringence constants for rail samples. Through gradual iterations of the laboratory sensor test platform, setup variability was reduced to 25°C.

On average, ⅓ of the error (20MPa) is due to measured variation in birefringence constants, whilst the remaining ⅔ (40MPa) are resulted from zero-offset variations. The 40MPa zero-offset error matches the error that a 2ns (0.5GS/s) digitiser would experience for a variation of ±4ns in the time domain. This implies that the zero-offset error observed is largely due to the digitiser. A higher sampling digitiser (20GS/s) is commercially available and should improve the measurement accuracy towards the 3°C target. Further work is required to isolate the other causes of variation and to replicate the results on rail in track.

Method B's feasibility under laboratory condition has yet to be proven and as such the method remains at TRL2.



Implementation and open questions

Further trials with a 20GS/s digitise should improve the accuracy of method B for measuring rail stress. It would be useful to show this benefit and to quantify the remaining variability that is caused by either setup variability or differences between rails such at composition, section size and wear or internal segregation.

There is still no certainty that ultrasonic methods will be able to achieve a blind stress-free temperature measurement at a level of accuracy that will be useful to the rail industry. Rail anisotropy exists and this is likely to have some effect on the measurement accuracy. This could push a reconsideration of the potential of alternative non-destructive methods for measuring stress-free temperature in rails.

Deliverable(s): D4.4

26 Measurement of track stiffness

Chen Shen, Zili Li, *Delft University of Technology / ProRail*

Background

Railway track stiffness is an important property closely related to track condition and maintenance. Track stiffness variations occur over time and space due to dynamic train loading and aging of track components. Track stiffness variations may further lead to geometry deteriorations and vibration problems. It is therefore essential to continuously monitor track stiffness variations, as well as related track component degradations, over time and space, so that preventive and targeted maintenance can be performed to reduce the life-cycle cost of rail infrastructures.

Various techniques exist for evaluating track stiffness from dynamic responses of the train–track system, including track-side and train-borne measurements. The track-side measurement uses sensors mounted on sleepers to measure the track stiffness at each sleeper support. Nonetheless, because of the cost of sensor deployment, the track-side measurement is more suited for discrete locations in the rail network of special interest, such as transition zones. To scan for track stiffness over a long distance, specialised measurement vehicles were developed. However, they can only measure at low speeds and require track occupation, thus not suitable for frequent measurements.

In comparison, train-borne measurements using in-service vehicles are more cost-effective and allow for more frequent surveys of the entire rail network. However, existing techniques are not able to measure the respective stiffness of different track layers, such as the ballast and railpad stiffness. In addition, existing train-borne techniques using in-service vehicles have seldom been validated by field measurement data.

Increased knowledge and implementable results

In project In2Track2, a method was developed that can simultaneously assess the stiffness of railpad and ballast from axle box accelerations (ABA) measured on in-service trains. The technique was validated in the lab. The objective of this study is to validate the method in an industrially relevant environment. To this end, the method is adapted and applied to real-world vehicle–track systems and validated through field measurements.

The test site was chosen at a railway bridge between Murjek and Boden on the Iron Ore line in Sweden, as shown in figure 26-1. Track stiffness variations from the transition zone to the bridge covering 10 sleepers (i.e., sp1 – sp10) were evaluated.

A vehicle-track interaction (VTI) model was developed and calibrated/validated by hammer tests and ABA measurements at the test site. Simulations were conducted with different combinations of railpad and ballast stiffness using the validated VTI model. As a result, quantitative relationships between track stiffness and measured ABA features were established, see figure 26-2 for an example.

Based on these relationships, the stiffness of each track layer is related to distinct ABA features, which enables multi-layer track stiffness evaluations. In particular, ABA exhibits higher sensitivity to the ballast stiffness in the low-frequency range (below 150 Hz), while the railpad stiffness has a greater impact on frequencies ranging from 150 to 1200 Hz.

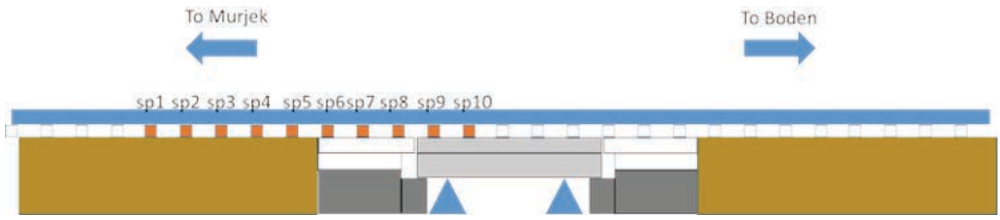


Figure 26-1 Schematic of the field measurement site

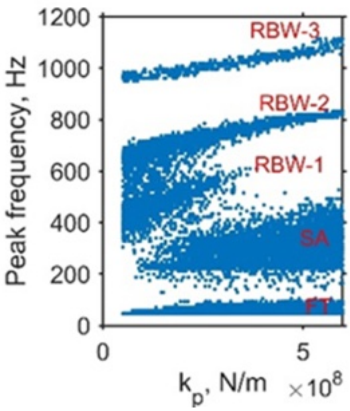


Figure 26-1 Relationships between railpad stiffness (kp) and peak frequencies of ABA.

Subsequently, data-driven models were trained based on the simulations to establish the inverse relationships, i.e., between ABA features and track stiffness. These data-driven models were used to evaluate the railpad and ballast stiffness across the 10 sleepers (figure 26-1) based on measured ABA features.

The results were compared with those evaluated by hammer tests. The stiffness variations evaluated by the ABA and hammer test exhibited a similar trend, indicating the change in supporting conditions in the transition zone. In addition, the stiffness values obtained from the ABA measurements are higher than those by the hammer tests due to the difference in loading conditions. It was also verified that the unloaded and loaded stiffness values identified in the study align with those reported in the literature.

Implementation and open questions

In future studies and practical applications, a more comprehensive understanding of the rate at which track stiffness changes can be gained by integrating frequent ABA measurements with in-track validations, utilising the techniques demonstrated in this study.

The technology can be used to monitor changes in track stiffness over time due to track maintenance activities (e.g., tamping) or seasonal effects (e.g., groundwater level and temperature). The technology could also be developed to detect spatial stiffness variations due to, e.g., different fastening systems and property changes in embankments or subsoil.

The technology can be further developed and demonstrated under different and more complex operational conditions, such as with the existence of rail discontinuities, at varying vehicle speeds and different levels of track irregularities.

Deliverable(s): D4.2

27 Influence of thermal loads on rail deterioration

Johan Ahlström, *Chalmers University of Technology / Trafikverket*

Background

Rail maintenance in terms of milling and grinding of the rail head has to be done with high efficiency since access to track for service is limited and costly. Machining off the top layer of the rail head should remove shallow cracks such as the commonly present "head checks", indentations and also correct the rail profile. However, especially high power rail grinding causes frictionally induced thermal input to the surface layer that can adversely affect the rail material properties. Rail repair welding or rail replacements are necessary when cracks go deeper. Local heating and cooling cycles have large effects on the material microstructure, strength and residual stresses. Imposing medium to high temperatures (ca 500–750°C) causes the material to relax the beneficial compressive residual stresses and work hardening present in the rail head surface layer and can also make the material softer due to spheroidization. Even higher temperatures (above ca 750°C) can cause phase transformations to martensite, resulting in a hard and brittle so-called White Etching Layer (WEL) that can be a site for crack formation. The peak temperature and its duration are most influential on the material property changes, and thus sets an upper limit for the acceptable frictional power on the surface during rail grinding. The studies presented here all investigate different aspects of those processes for pearlitic rail steels to improve possibilities for prediction of rail deterioration under the influence of thermal loads.

The influence of thermal loads on rail surface deterioration are studied in experiments combining large plastic deformation (to mimic the actual microstructure in the top layer of the rail), varying mechanical stress and strain (representing the loadings in operation) and thermal loading (representing frictional heating). To examine the different phenomena, these are applied in different combinations, for example by pre-deformation followed by subsequent heating, or simultaneous deformation and heating, so-called thermo-mechanical loadings. The results are interpreted and compared to observations from field.

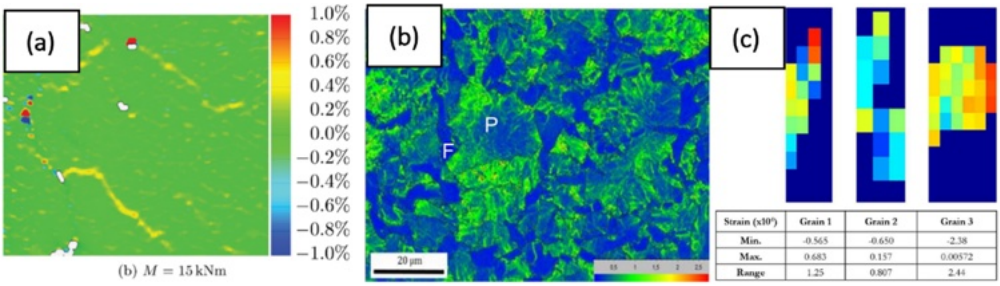
Increased knowledge and implementable results

The first step should be to get to know your enemy, in this case the surface cracks. Thus, first try to estimate the quality of the rail surface, and identify which method is required to re-furbish. Is it enough with a mild grinding, or is milling or even rail replacement required? A feasibility study showed it could be possible using the weight of the train itself and a digital image correlation (DIC) setup to judge the depth of cracks (figure 27-1 a). Maintenance should remove all surface cracks, without generating excessive surface temperatures.

Another important finding was that thermo-mechanical loadings, which happens during rail welding and in block-braking of railway wheels, causes responses in the material which cannot be readily simulated without experiments that expose the material to similar combined loadings. One reason is the mechanical response arises from a combination of a time-dependent material behaviour active only at high temperatures and permanent softening that remains after heating.

Complementary studies were needed to quantify such softening with electron microscopy and synchrotron diffraction techniques; see examples in figure 27-1b and c.

A further insight originated from experiments using laser heating to imitate frictional heating during grinding or heating during repair welding. Both rail (R260) and wheel (ER7T) steels were investigated regarding microstructure, hardness, and residual stress after local heating. Trends are the same for the wheel and rail steel with the two methods, with a full martensitic transformation in a limited volume, giving high hardness and in case of overlapping runs local tempering with following loss of hardness. However, the rail material developed more compressive residual stresses in the experiments, compared to the wheel steel. The laser heating method is judged to be suitable for simulation of grinding induced thermal damage.



Strain (x10⁻³)	Grain 1	Grain 2	Grain 3
Min.	-0.565	-0.650	-2.38
Max.	0.683	0.157	0.00572
Range	1.25	0.807	2.44

Figure 27-1 (a) Cracks on rail surface identified with DIC [1]. (b) Local misorientations in wheel steel ER7T after heat treatment (ht) at 500 °C; ferrite grains (blueish) have smaller gradients than the pearlite [2]. (c) Residual strains in ferrite grains (ER7T after ht at 500 °C) measured by synchrotron X-ray diffraction [3].

Implementation and open questions

The improved knowledge on material behaviour combined with advanced FE simulation can help judge the effects of rail treatment and estimate limits for different methods regarding depth of material removal that can be applied during treatment. For grinding operations, a higher grinding depth in one pass leads to higher heat input which can lead to thicker and thereby detrimental thermal damage. This is counteracted by decreasing the grinding depth and increasing the operational speed for a last pass. In rail milling, depth limits are less problematic as heat input is generally much lower. Our work concludes that the properties of the material at depth 1–1.5 mm below the surface is almost as hard, has a less deformed microstructure and lower crack densities than the original surface. Use of the techniques developed will be resources for coming scientific studies, and parts could be implemented for wider use by commercialisation.

Deliverable(s): D3.3

28 Degradation mechanisms of bainitic rail steel

Thibault Lesage, *IRT Railenium*

Background

Rails are commonly made of pearlitic steels, which are well known since decades and have perfectly fine wear and fatigue resistance. However, with the increase of train tonnage and speed, alternative solutions are looked for. Carbide-free bainitic steels are one of these solutions and present outstanding fatigue resistance (figure 28-1).

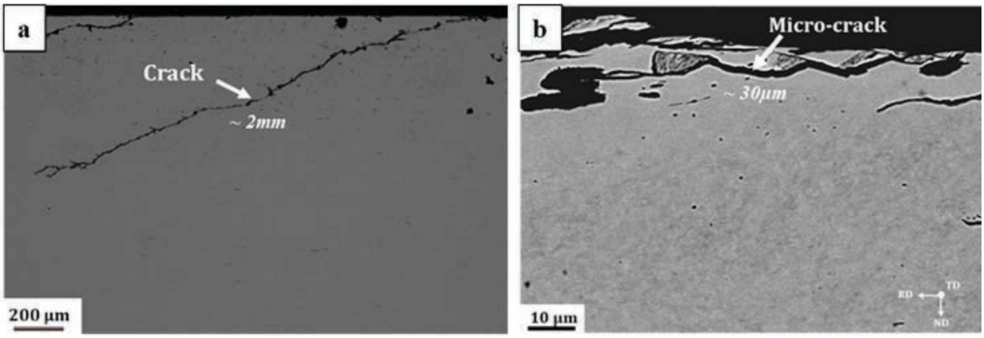


Figure 28-1 a- Typical rolling contact fatigue (here, head check) observed in R260 pearlitic steel, b- Micro-crack of less than 30µm observed in carbide-free bainite for identical solicitation.

Their main weaknesses are a lower wear resistance than classical pearlitic steels, a poor weldability sometimes leading to a loss of shunt around the weld and a lack of understanding of the degradation mechanisms. Work in In2Track and In2Track2 allowed a better understanding of these mechanisms, emphasising the importance of TRIP effects (austenite transformation into martensite), on wear and fatigue resistance. Microstructure was thus considered critical and further studied in In2Track3.

This project aims to identify the reasons behind the poor weldability of bainitic steels, which is at the moment the major limitation of these steels. If weldability was to improve, the use of bainitic steel could be way more widespread, potentially becoming a more standard solution for applications where fatigue resistance is particularly needed. This includes curves, switches and crossings, where base material (rail not affected by the welding process) bainitic steel already vastly surpasses classical pearlitic steel.

Welding of bainitic steels is known to be poorly repeatable, with hardness usually dropping close to the weld, inside the so-called Heat Affected Zone (HAZ). It leads to excessive wear and stress concentrations which, in turn, induces high maintenance costs. However, the very reasons why the HAZ behaves poorly is still unclear, which makes improvements of either welding process or rail production difficult. Thus, better understanding the consequences of welding on the surrounding Heat Affected Zone makes perfect sense and is the main goal of this work.

Increased knowledge and implementable results

Two distinct carbide-free bainitic steels have been studied in this work. One is known to be poorly weldable and is consequently rarely seen in field. The second one is a successful steel that presents a good weldability, whilst the reasons beneath it are yet unclear. For readability purpose, the first one will be referred in this text as Poorly Weldable (PW), while the second will be referred as Highly Weldable (HW).

Starting with HW grade, we observed after welding similar hardness in both the base material, weld and HAZ. Due to the thermal history (temperatures of more than 2000°C inside the weld), microstructures vary between each of these zones. Nonetheless, the crystallographic phases are mostly identical. No geometrical defects nor chemical heterogeneities are evidenced, and mechanical properties are mostly similar.

Going now towards PW grade, the story vastly differs. While no geometrical defects nor chemical heterogeneities are observed, the hardness collapses inside HAZ. Interestingly, this hardness loss is always located at identical distance from the weld. As a result, the thermal history of the HAZ, and especially this specific area, have been investigated, both numerically and experimentally. It is found that this area corresponds to a critical temperature where phase change occurs. Austenite, which is the main contributor to the high fatigue resistance in the base material, is transformed. The main crystallographic phase is changed, leading to massive loss of hardness and wear resistance. Resulting HAZ hereby become a weak spot and is subject to future degradation.

Comparing both grades enabled us to identify the main chemical differences and understand the role of these differences at this critical temperature. It results in the proposal of an improved version of PW grade, which could hopefully meet the standards of HW grade.

Implementation and open questions

Most of the upstream understanding of the problem has been addressed during this project. Nonetheless, this has yet to be translated into actual improvements of the PW grade. Theoretical changes have been proposed and are yet to be tested. If these tests are successful, the mechanisms proposed will be considered as validated and further modifications of bainitic steels could be undertaken in a more informed manner. This would induce a progressive change in the use of bainitic steels in European railways, which would eventually support heavier and faster trains.

Several open questions arise from this project. The main one is related to the critical temperature, which is unavoidable in thermite welding. The geometrical position where this critical temperature is observed could be shifted but the rail would nonetheless be exposed to it for a prolongated time. Thus, the approach of modifying chemical composition chosen in the end of the project could be an answer but its efficiency and reliability is hard to predict. This could be coupled with modifications of the initial thermal history, during rail manufacturing, but this induces stronger modifications of the base material overall performance and numerous tests would be needed.

Deliverable(s): D3.3

29 Wheel-rail friction measurement in the V-Track

Zhen Yang, Jan Moraal,, Zili Li, *Delft University of Technology / ProRail*

Background

Friction/adhesion management in railway networks is a challenge for infrastructure managers and railway operators. Friction/adhesion at the wheel–rail interface influences the braking and traction performance of railway vehicles and the formation of wheel and rail defects. A minimum level of friction/adhesion must be guaranteed to ensure appropriate braking and traction of vehicles, whereas high friction/adhesion increases wear and rolling contact fatigue (RCF) of wheels and rails, noise emissions and carbon footprint (transportation energy consumption). A crucial part of friction/adhesion management is to reliably measure the wheel–rail friction levels and creepage. A train-borne tribometer is desired because the wheel-rail friction level depends on, among others, the normal contact load and speed. A light vehicle will thus experience adhesion different from a heavy train, and the accuracy of hand-pushed tribometers is adversely affected by scaling and low speed.

Aiming to contribute to the development of a train-borne tribometer for friction/adhesion management, this study conducted a comprehensive lab test in the V-Track in the Railway lab of TU Delft. The V-Track is a downscaled wheel-rail contact test rig consisting of a 4-meter-diameter ring track and 1~4 wheel assemblies running over it with well-controlled and measurable normal load and friction forces. The coefficient of friction (COF) was measured with two schemes: 1. Increase the angle of attack (AoA) to get friction saturation in the lateral direction and 2. Increase the traction/braking torque of the wheel to get friction saturation in the longitudinal direction. The wheel-rail contact forces in the three directions, AoA, wheel rolling speed and rotational/circumferential speed, and traction/braking torques were measured and analysed to obtain the COF of the V-Track.

Increased knowledge and implementable results

Figure 29-1 shows the adhesion levels, in terms of adhesion coefficients (ACs), measured along one V-Track circle in the dry clean condition using scheme 1. The AC is the ratio of the wheel-rail friction force to the normal load, and is thus bounded by the COF. It shows that the AC increases with AoA, and when the AoA is sufficiently large, a trivial increase of AC, if any, is observed with the further increase of AoA . The friction saturation is then considered to be reached and the AC equals COF, which is about 0.45. The measured ACs oscillate due to the presence of wheel/rail surface irregularities. The adhesion levels measured in the same dry clean condition using scheme 2 were analysed as well and compared to the results obtained using scheme 1. Likewise, a trivial increase of the AC was observed with the further increase of wheel torque when the friction saturation was achieved. The corresponding AC, i.e. the COF, is also 0.45, in line with the results measured with scheme 1. The COFs measured by the two approaches can thus be cross-validated.

An interesting finding was also provided. The measurement conducted in a different, also dry clean, track condition showed significant stick–slip contact behaviour when using scheme 1. That track has a lower level of surface roughness/irregularity, indicated by a lower COF=0.35 and less oscillation of ACs for the testing cases without friction saturation. The comparison between the two measurements suggests that the surface roughness/irregularity may act as turbulence and prevent the occurrence of stick-slip.

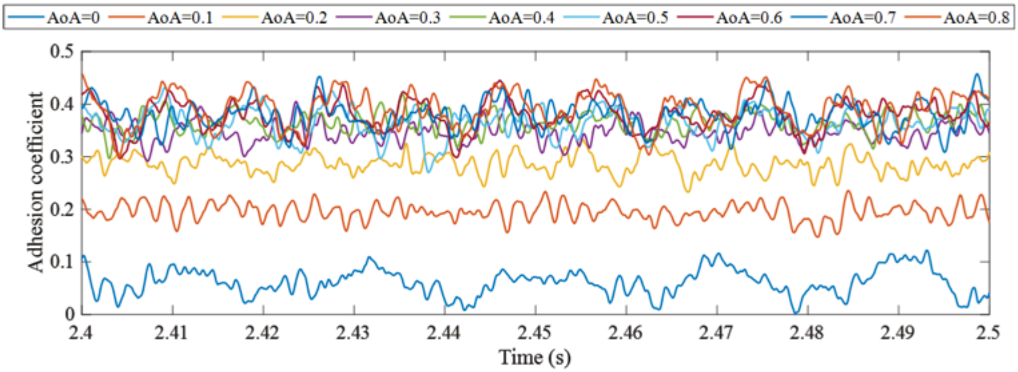


Figure 29-1 Increase of AC with AoA and friction saturation

This study proves the reliability of the wheel-rail friction/adhesion measurement on V-Track by cross-validation of the results obtained with two the measurement schemes, enhances the understanding of the friction saturation process with increasing torque and AoAs, and discovers that under dry contact conditions, the occurrence of stick–slip is determined or affected by wheel–rail surface roughness/irregularity. These may contribute to the development of a train-borne tribometer as well as the mitigation of wheel–rail sliding and squeal by e.g. optimising train acceleration, braking and curving behaviour.

Implementation and open questions

A torque modulation concept will be employed for the development of a no-sliding train-borne tribometer, considering that reliable measurement of wheel - rail creepage is challenging, especially in field conditions. The concept is based on the fact that acting as variable damping, wheel–rail friction causes a phase difference between the wheel torque and angular velocity. This phase difference will be measured in the modulated condition and used to derive the friction behaviour, e.g. in terms of the slope of the creep curve.

The concept has been verified via numerical simulations and will be experimentally validated in the lab. After that, a prototype of the train-borne tribometer, which can reliably measure wheel-rail contact force, wheel torque and angular velocity, is expected to be developed. Note that although the dependence of the friction level on contact stress and rolling speed are considered in the lab test, the V-Track test rig may not fully reproduce real-life wheel - rail contact in the field with greater variations in, e.g. the loading amplitude, contact geometry and environment. The difference in contact behaviour between the downscaled V-Track test rig and full-scale wheel - rail contact will be further investigated.

Deliverable(s): D3.4

30 Follow up performance of innovative track solutions

Anders Ekberg, Elena Kabo, *Chalmers University of Technology / Trafikverket*

Background

The topic of how to review and follow up performance of innovative track solutions is a topic which is often neglected – too often massive efforts are put on trying to predict the performance of an innovative solution, but there are very limited resources to evaluate the actual outcome. This is especially the case if the outcome can be assessed only after several years, which is often the case when it relates to robustness, deterioration, and life cycle costs.

This inability to follow-up performance has been identified as one of the main obstacles to operational implementation: If benefits/drawbacks with a solution are not evaluated it is not possible to draw conclusions for further development. It is also more difficult to motivate new investments due to the uncertainties in cost/benefit analyses.

Two topics are studied in In2Track3: upgrading of the heavy haul Iron Ore line (Luleå–Narvik) in Sweden/Norway from 30 to 32.5 tonnes axle load, and a detailed follow-up on the installation of an innovative slab track solution on the same line with focus on transition zone behaviour. The latter is described on page 44-45 (in addition there are more chapters dealing with the innovative slab track solution).

Increased knowledge and implementable results

To follow-up performance of any innovative track solution the requirements that the innovative track solution – be it full track, or component – must/should fulfil need to be specified. For upgrading the requirements are essentially that operations should be safe, and deterioration levels sufficiently low to make the upgrading economically feasible. These requirements must then be related to measurable operational load and performance parameters. In the evaluation of the transition zone, important parameters were identified as wheel loads and settlements with limit values governed by regulations.

The next step is to establish a baseline – what is the status before the innovative solution is introduced. For the transition zone this was taken as values after installation. For the axle load upgrading establishing a baseline proved to be a challenge as discussed below.

The third step is to follow-up how the performance is affected by the innovative solution. For the transition zone this was made using wheel load and settlement measurements. The evolution of these values was then compared to nearby track sections.

As mentioned, one test scenario featured an increase in axle load from 30 to 32.5 tonnes on the Iron Ore line in northern Scandinavia. Focus was on how the increased axle load affected track structure and running gear in terms of mechanical deterioration. For parts where an increased load will essentially cause a decrease in safety margins (e.g., bridge integrity and slope stability) follow-up is more uncertain and needs to rely on indirect measurable effects.

To establish a baseline proved to be very complex for several reasons: The increased axle load was introduced in steps with initial test train operations, which excludes the use of an introduction date. In addition, track quality and track status varied significantly over the years. This was linked to several factors such as maintenance volumes, variations in track inspection reports, operational variations (tonnage, altered wheel/rail profiles etc), and variations in climate. From a simulation perspective – where the influence of the altered operational conditions is established from numerical analyses – establishing a baseline is however straight-forward since it can employ a "nominal" track status and axle load before upgrading.

Figure 30-1 Left: Switch & crossing at the Iron Ore line. Right: Plastic deformation of the tip of the switch rail.

Follow-up on performance also turned out to be challenging. Even the seemingly obvious question of how much the axle load had actually increased was difficult: although the allowed axle load was 32.5 tonnes, the brake system imposed a limit of 31 tonnes with a stricter error margin than before upgrading. The result was that the average axle load did not increase at all on the southern Iron Ore route (Kiruna – Luleå) but did increase on the northern route (Kiruna – Narvik). Follow-up on track deterioration turned out to be very challenging for similar reasons as those that complicated establishment of a baseline.

What could be established was the increased wheel damage (surface initiated rolling contact fatigue) on a test train with increased axle load. Here numerical analyses predicted reductions in rolling contact fatigue lives as those observed. It is thus reasonable to assume that for predicted rail damage, consequences of the increased axle load can be established from numerical analyses in a similar way as for the wheel damage. An interesting aspect is the required input data for such analyses: For subsurface initiated rolling contact fatigue the increase in vertical load is sufficient, for surface initiated rolling contact fatigue also lateral forces are required, and for wear also the wheel–rail slip is required. The complexity and uncertainty increase in a similar relation with vertical loads fairly straight-forward and slip highly complex to measure and validate.

Implementation and open questions

The general approach has been operationally demonstrated in In2Track3 regarding transition zones. Here both baseline and key performance parameters were defined and measured.

The more general case of axle load upgrading is more complex. The current study has outlined ways to perform follow-up using combination of measurements and simulations. Increased understanding of the relations between measured data, numerical simulations, and actual deterioration is severely needed.

Deliverable(s): D3.3

31 Drainage management system

Ehsan Kazemi, Yiqi Wu, Simon Tait, Andrew Nichols, Jamil Raja, *Network Rail*

Background

It is increasingly recognised that effective control of water and proper understanding and maintenance of drainage assets is fundamentally important for the safe operation of the rail network. Inadequate drainage capacity or a loss of drainage system performance can result in many failure mechanisms that affect other railway assets. This could include the long-term degradation of the stiffness of materials forming the track support system, and the stability of trackside earthworks. An impaired drainage system can thus result in significant damage to other railway assets and risk of disruption to train operations. Hence, it is important to investigate the effect of the condition and inferred performance of drainage systems on the potential for the failure of a wide range of railway assets in response to rainfall and climate change at a country-wide scale.

One way to determine hydraulic performance is to build a detailed deterministic hydraulic performance model, but to do this for all railway drainage systems is highly costly as it requires accurate and detailed site-specific asset data. Given the current incompleteness of the asset inventory in some of Network Rail's regions, Machine Learning (ML) approaches were developed to analyse historical data of asset failures (and non-failures) in order to explore and quantify linkages between rainfall parameters, other railway asset properties, drainage system condition, and failures. This avoids requiring a full hydraulic model.

The approach follows a multi-stage process. First, Self-Organising Maps (SOMs) are used to explore the relative strength of relationship between different parameters that influence the underlying causes of (a) track flooding, (b) earthworks failures and (c) wet beds, that are linked to railway drainage assets. The evidence of strong relationships is used to identify highly relevant parameters, which are then used to calibrate a Random Forest machine learning model to predict the likelihood of failures occurring at any location.

Increased knowledge and implementable results

The results of the study demonstrated that:

- The risk of track flooding can be best estimated based on the average condition of the nearest drainage system within 100m, the 5-day antecedent rainfall volume, and the type of nearby earthworks, with a prediction accuracy above 73%.
- The risk of rainfall-driven earthworks failures can be best estimated based on the average condition of the nearest drainage system within 100m, the 5-day antecedent rainfall volume, and the type and material of the earthwork, with an accuracy above 72%.
- Wet beds prove to be difficult to predict, only showing a clear relationship with track geometry (which likely occurs as a result of the wet bed itself) but limited relationships with a wide range of potential causal factors. It was postulated that the underlying cause of wet beds may be due to a number of distinct failure pathways that have different causal factors.

Models have been applied nationally showing that individual asset failure risks can be identified, and this information made available in a range of formats, for example providing a heat map of drainage-related risk to assets (figure 31-1).

Implementation and open questions

The ML based failure prediction algorithms were coded to be used operationally by Network Rail.

Matlab based software was developed so that NR staff could implement the asset failure prediction approach at an operational level for track flooding and drainage related earthwork failures.

The software was supported by fully documented methods to obtain suitable training and validation data, and also a risk tool that allows Network Rail staff to examine the failure likelihood of assets for various external scenarios.

This makes the ML based modelling approach TRL 7 within NR.

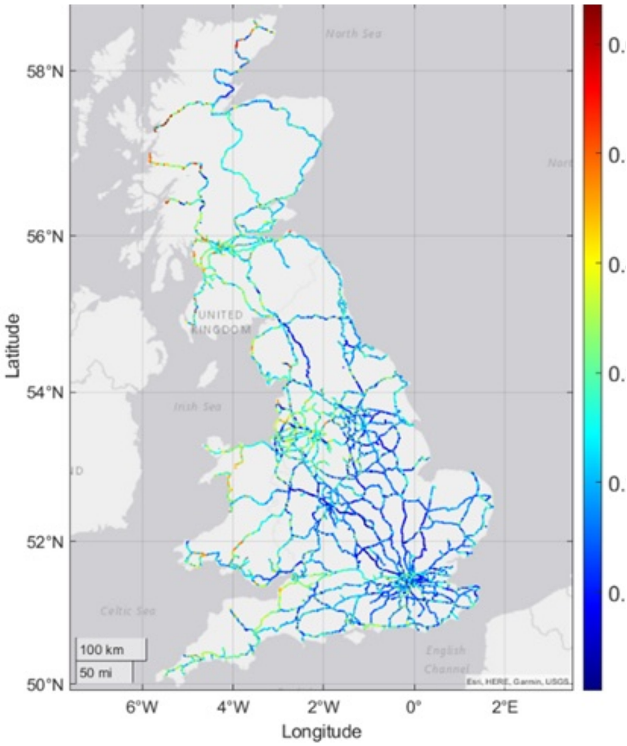


Figure 31-1 Probability of failure for track flooding based on 5-day precipitation

Some recommendations for future research:

- Enhance drainage data accuracy, especially asset location and condition records, so that the interaction between drainage and other types of assets can be better investigated.
- There is a need for systematic data gathering on causal factors of failures, such as local drainage system capacity and catchment characteristics.
- Further efforts are necessary to integrate failure risk models seamlessly into NR's decision support systems.
- Further research is needed to identify wet bed failure mechanisms. Initially it would be advisable to determine whether there are different forms of wet bed that can be characterised by different physical factors.

Deliverable(s): D3.1 & D3.3

32 Feasibility of non-chemical alternative for vegetation control

Baptiste Bonzon, *SNCF Réseau*

Background

Vegetation management on tracks and their surroundings is essential to ensure safety and regularity of traffic. On the SNCF Réseau network it represents a land of 110 000 ha including 34 000 ha for tracks and safety paths.

The presence of vegetation on the network can lead to some repercussions as avoid functioning train detection in track, blind or damage signal installations and security equipment along the track, clog up track drainage, provoke fires, cause traffic interruptions due to fallen trees on the track, provoke spinning and jamming of wheels, avoid safe walking on the safety path section for infrastructure manager workers or passengers, or blind visibility of approaching trains and thereby increase the risk of accident particularly for maintenance teams.

The vegetation management policy is not the same, depending on security standards. The aim for the green outlands is to maintain a controlled shrub cover on the surroundings areas and a grassland cover on the close strips. On the track and safety path, which is the core of the infrastructure, the aim is to be as close as possible to the zero vegetation for security reasons.

SNCF Réseau has initiated two programs to find solutions and be able to continue to ensure the safety of people and the movement of trains in terms of vegetation management: one is focused on the end of 2021 with the end of the use of glyphosate, and the other is dedicated to finding long-term solutions for vegetation management solutions on tracks and safety trails without using synthetic phytosanitary products. In this study, the focus is on vegetation management using electromagnetic waves.

Increased knowledge and implementable results

Laboratory tests have been carried out to study conditions for killing vegetation in an open environment. The effects of different electromagnetic wave exposure on vegetation that grow in track have been studied (thermic, non-thermic or a combination of both). The effects of EM waves on vegetation turned out to be different depending on if it is a non-thermic or a thermic spread.

A non-thermic spread EM wave whose principle is the emission of an EM wave on the plant emitted through an aerial cone which doesn't transmit any heat to the plant didn't show any phenotypical effect on the plant, but the plant delivers an electric signal corresponding to a biochemical stress resulting from the EM wave.

Figure 32-1 Non-thermic exposition study setup

The effects of a thermic spread EM wave exposure, whose principle is the same as in the first investigation, but with a type of wave that heat the plant, showed that the core parameters to get the aimed effect, which is the vegetation destruction are power, distance, exposition duration, and the aerial cone dB gain.

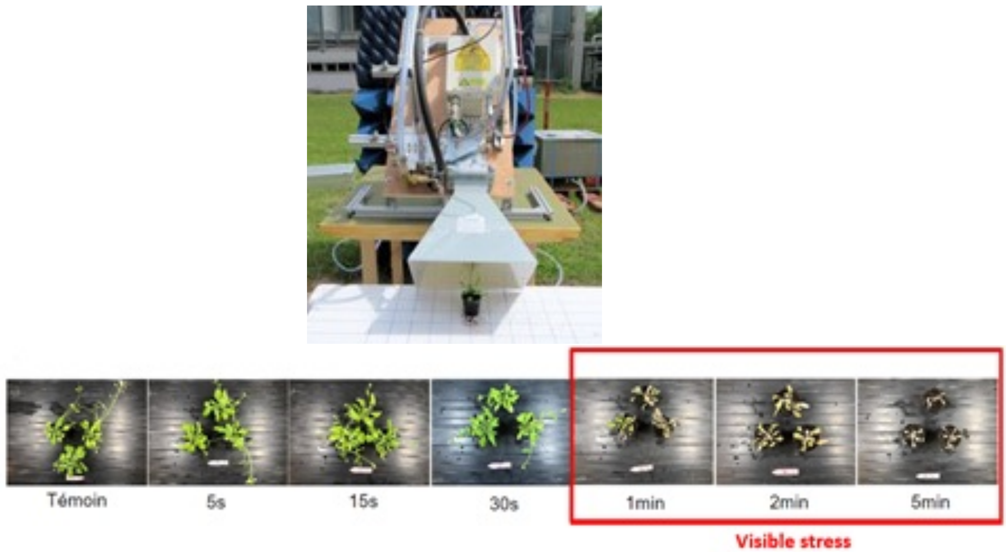


Figure 32-2 Thermic exposition study setup and example of results

The combination of thermic and non-thermic spread EM wave, whose aim was to see if the combination of the first two ways of exposition can lead to a destruction maybe quicker than both taken independently, showed no additional effect compared to thermic spread EM wave exposure alone. A lethal effect on the vegetation was obtained after the same time with combined exposition and thermic exposition for the parameters considered.

The leaf targeted by the thermic direct EM wave directly lose their strength and die. Repeated on all leaf the death of the plant is observed just after the contact between the EM and the plant.

Implementation and open questions

The results of this study answer to the initial aim of finding methods using electromagnetic wave to kill the vegetation. However, it's still too early to think about a prototype, even if it has a strong potential. Deeper research about the thermic EM wave exposure has to be carried out. On one part, about the biological reaction in the plant after the contact between the EM wave and the leaf or root. On the other part, industrial use cases to size the emitter (power needed, how to extend contact points on the plant, time needed to cover the entire plant…) have to been determined considering railway constraints (track equipment, minimum speed on main tracks, catenary posts on safety paths…). For example, could we imagine a train running at 60km/h and covering all the track-safety path width with an EM wave emitter?

The aim of a second study would be to define use cases and determine physical and technical conditions to answer to it with thermic direct EM wave exposure machine.

Deliverable(s): D3.3

33 Ballast recycling

Vincent Chartie, François Nader*, IRT Railenium*

Background

Ballast is used to maintain the stability of railway tracks under traffic loads and distribute these loads to the foundation soil below the sleepers. The magnitude of the cyclic loading generated by passing trains has a significant effect on the ballast grains, which translates into a settlement of the track geometry. To counter this effect and rectify the highly critical geometrical aspect of the track, a maintenance procedure is employed, consisting of tamping the ballast bed. To preserve and optimise the behaviour of ballast grains, multiple variables must be tuned and evaluated. The goal of this research was to identify these variables, and evaluate their influence on safety, costs, and environmental impact of railway traffic.

The objective consisted in developing a numerical tool that allows to accurately predict the behaviour of ballast grains, while considering the state of the grains (fresh or worn).

In fact, the design of ballasted tracks is still largely empirical, and significant levels of settlement take place, mainly due to shape alteration of the ballast grains supporting the tracks. The grains undergo abrasion which reduces sharp corners and reduces the probability of grains interlocking. This in turn leads to a weakened resistance to settlement and lateral displacement. Furthermore, for sufficiently large loads, the ballast grains break into multiple fragments which alters the bulk behaviour.

The coarse size of ballast grains means that the scale of experimental tools required to conduct the standard studies to characterise the material's behaviour is much larger than what is usually available in geotechnical laboratories. This translates into a much higher cost for experimental studies. Even though numerical simulations need to be calibrated, they are usually less costly and offer an in-depth analysis of the phenomena, which complements standard experiments when analysing ballast behaviour.

Increased knowledge and implementable results

The numerical tool developed in this project can predict the ballast behaviour depending on the ballast bed shape and the loading applied by the trains. It is based on a Discrete Element Method software called BlazeDEM-GPU in association with the use of Graphic Processing Units. This enables calculations much faster than Finite Element software with Computational Processing Units.

To begin this work, the influence of the shapes of the ballast grain on the simulation results has been studied. Grains of ballast were 3D scanned and used in the models. Spherical grains and different levels of grain geometry simplification were tested and compared to test results in the case of a pull-out test which consists in applying a lateral force on a sleeper which is embedded in a ballast bed. It appears that the use of spherical grains, even with numerical artefacts, could not provide accurate results whereas simplified 3D scans give better results. Therefore, an algorithm for reconstruction and simplification of the geometry was designed to obtain geometries representative of the real grains while reducing the number of faces to accelerate numerical calculations. Nevertheless, the results in terms of overall resistance are still lower than the experimental results, and a number of improvements have been suggested to enhance the performance of the method (modification of the contact law, more realistic sleeper geometry etc).

In addition, to make the numerical model more powerful, and to add improve its ability to reproduce the real behaviour of the ballast, an experimental study of grain crushing tests was performed. The experimental data obtained is coupled with an algorithm that defines the geometries of the fragments resulting from the breakage of a grain, to simulate the breakage in the simulations.

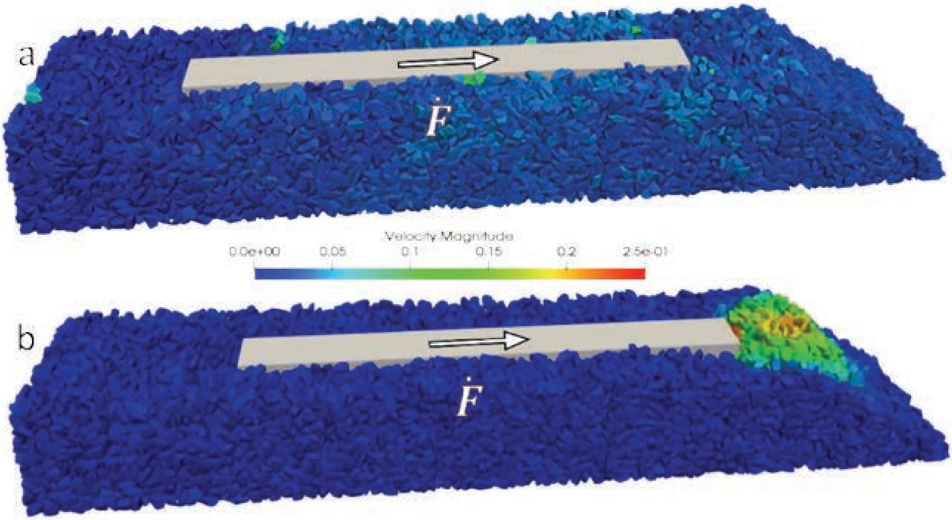


Figure 33-1 Sleeper embedded in ballast layer, 32000 grains using reconstructed scans to simulate ballast, a) Initial setup of pull-out test, b) Final state after pulling out sleeper

Implementation and open questions

This methodology demonstrated promising results and could be applied for several use cases. For instance, it could be implemented to make simulations of cyclic loading of multiple sleepers resting on ballast in order to replicate train traffic loading and to predict long-term behaviour of ballast under actual conditions. The aim would be to provide decision support for maintenance considering the specificity of ballast characteristics.

Moreover, ballast bed configurations could be simulated to evaluate their performances and assess the potential of reusing ballast grains in specific ratios at specific locations in the ballast bed. This would allow to improve the ballast recycling process by classifying used ballast and evaluating the potential of each class in future structures and infrastructures, while also providing an optimised strategy of reuse of ballast.

The tool could also help to analyse the effect of different tamping parameters and settings to identify the optimal tamping configuration resulting in reduced damage to the ballast grains. This means that this methodology could be used by either infrastructure managers, railway maintenance companies or companies that design or use tamping machine.

Deliverable(s): D3.3

34 Rail machining strategies

Anders Ekberg, Erika Steyn, Björn Paulsson, Elena Kabo, *Chalmers University of Technology / Trafikverket*

Background

During operation, passing wheels will wear, the railhead and may cause crack formation. The main objective of rail reprofiling is to restore the railhead profile and remove damaged material as efficient as possible without causing adverse effects. This is a challenge due to the current situation of increased and more aggressive traffic with more need for reprofiling, but less access to the track. Consequently, improved strategies are needed.

To this end, the work in In2Track3 consisted of the analysis of a questionnaire to the UIC Track Expert Group to investigate best practice in a European context, a study on machining techniques and technologies to identify the currently best practices and potentials for enhancement, and an in-depth investigation of consequences of (not) fulfilling rail machining objectives and of the detrimental effects rail machining have. In addition, a study was made on how rail machining efficiency and impact could be evaluated.

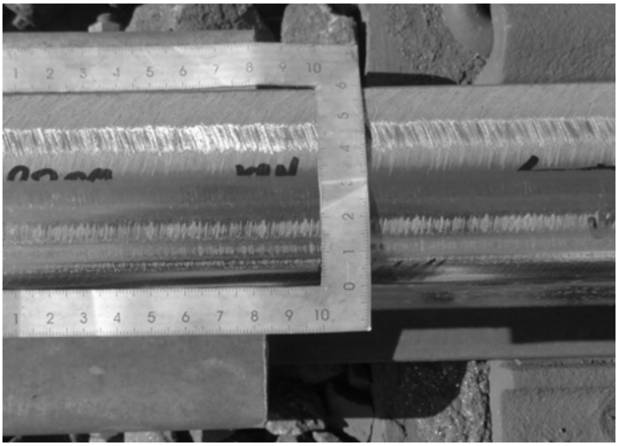


Figure 34-1 Recently ground rail

Increased knowledge and implementable results

Investigations of best practices among infrastructure managers reveal that they consider surface treatment beneficial to extend rail life. The main benefits are controlling rail head geometry and surface defects, and thereby increasing the rail life. There is however very scarce information on how large the beneficial effect is. Grinding is the predominant surface treatment method with milling used in special cases like corrective maintenance. Grinding and milling are therefore mainly seen as complementary techniques. Here grinding has the benefit of speed and costs, whereas milling prevents spark formation, can machine at a larger depth, and leaves a smoother surface (cf. the grind marks in figure 34-1).

The survey of rail machining technologies, methods, and techniques identified several configurations and operational parameters that will affect the final rail machining result. The magnitude of influence of these parameters, and in particular the interaction between them is often not well understood. This is aggravated by the fact that there is limited operational experiences from controlled operations featuring various surface treatment methods.

Regarding consequences of (not) fulfilling rail machining objectives, remaining surface cracks and other defects will decrease the operational life of rails. The current level of knowledge and predictive abilities only allow for a qualitative analysis of this decrease in RCF life. The influence of removing the work hardened and damaged surface layer is likely to be minor but beneficial. There is however limited research on mechanisms and magnitudes of this influence. Where artificial lubrication is used, lubrication directly after grinding is recommended to restore friction levels and prevent RCF crack initiation. For rail grinding related roughness there is a significant lack of knowledge regarding how different parameters influence time for run-in (and induced damage during this time), saturation levels regarding friction, influence on RCF life etc. Two interesting questions here are:

- How interrelated is a decrease in RCF life to an increase in friction?
- What is the influence of scale effects when twin-disc test results are transferred to full-scale wheel/rail contacts? Note here that roughness doesn't scale, but curvatures of contacting surfaces (and contact patch sizes) do.

In addition, transfer of knowledge (from experiments, tests and field experiences) is hindered by an inability to describe and account for variations in tribological conditions between investigations and the difficulty of fully controlling operational parameters in full-scale grinding.

Regarding detrimental effects of rail machining, thermal power is becoming a key bottleneck that limits material removal rate. How that relates to grinding parameters is today not fully understood. A key question is how transferrable the relatively few tests in the literature are to other operational conditions. To this end, current simulation abilities need to be enhanced and supported by well designed (physical and laboratory) tests. This can also improve the currently very vague directives in the standard EN 13231-2:2020 on allowed thermal input.

Implementation and open questions

A summary of this research has been published in a scientific paper. A significant barrier for implementation is the current lack of knowledge and predictive models which limits possibilities to estimate effects of altered rail machining. This restrains development and limits transfer of empirical knowledge between different operational scenarios and translation of (scaled) experimental tests to (full-scale) operations. The restricted ability to optimise rail machining is also likely to be a major reason as to why the amount of grinding and milling currently varies significantly between infrastructure managers: If it is not possible to quantify benefits of altered machining strategies, it is difficult to motivate modifications and avoid cuts in budget and track access.

That being said, research is progressing, and important parts have been carried out in In2Track3. Examples are research on the influence of thermal impact on rail integrity (see Brake rig testing of generation and evolution of wheel defects, section 45), the growth of rail cracks (see Prediction of crack growth in the rail head, section 48), and the development of urban grinding machines see ATMO urban grinding machine to reduce noise and vibration in section 73).

Deliverable(s): D3.3

35 Rail repair by cold spray additive manufacturing

Thibault Lesage, *IRT Railenium*

Background

Rail repair is a problem of tremendous economic importance, since each rail removal leads to traffic interruption and maintenance costs. Most of the time nowadays, rail is repaired by cutting of the rail, removing it, and welding a new rail instead. This is a time consuming and expensive process, inducing numerous difficulties in the railways industry. While alternatives do exist, there still is a long way to go before they become standard.

This project lines up to this trend to propose alternative ways to repair rails. The process chosen, cold spray additive manufacturing, presents high potential gain but is extremely challenging. The process consists in supersonically spraying at low temperature a rail powder into a substrate (here, the damaged rail), building up a strong and adherent deposit. This technique has proven to be efficient in the aeronautics and space industries, due to its low temperature and high deposition rate. However, in these industries, cold spray is used for ductile materials, such as aluminium, which is extremely different to the stiff steels used in railways. Since the process leans on powder deforming on the substrate during impact, the difference in ductility plays a vital role. To our knowledge, very few attempts of cold spraying pearlitic steel such as the ones used in rails have been described in the literature.

However, if cold spray could be successfully implemented for rail repairs, repair time and cost would be greatly reduced, since only the damaged area is removed instead of the whole rail. Moreover, the problematics associated with welding, especially inside the heat affected zone, would be suppressed due to the low thermal input of this process. As a result, this project is a proof of concept of cold spray repair in railways industry and aspires to improve the current repair strategy.

Increased knowledge and implementable results

Cold spray demands a fine control of initial powder, initial and final heat treatments, as well as process parameters. Since few, if any, work deal with this type of steels with cold spray process, numerous optimisations were to be performed. Rail powder does not exist in the industry and has been produced on demand. Initial trials of cold spraying showed a poor adhesion, with most of the powder bouncing off the substrate. Numerous improvements have been performed during the project, working on initial heat treatment for ductility, process parameters for deposition rate and deposition ratio, and final heat treatment for adhesion and mechanical properties. It results in the production of a repair of over one millimetre thick, which could easily be built up thicker by increased duration. Adhesion and interface between substrate and deposit are of good quality. Resulting microstructure is similar to the substrate and, while more tests are needed, mechanical properties are encouraging. Very few porosities could be detected, even at the interface between substrate and deposit. The repair of an actual rail, presenting deep spalling defects which would usually be repaired by rail cutting and welding, is forecasted for early 2024 (figure35-1). This physical demonstrator will confirm the feasibility of the cold spray process for rail repair.

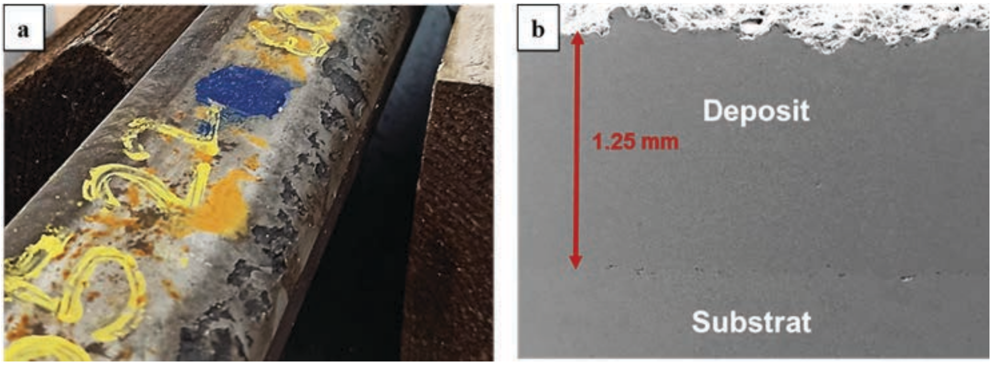


Figure 35-1 a- Physical demonstrator to be repaired, showing deep and numerous spalling defects. b- Typical repair achieved on laboratory test samples

Implementation and open questions

There are several potential next steps that can be engaged in parallel: Improving the cold spray strategy, using 5 axes for complex shape geometry would greatly improve the versability of this method. In a long-term development, it could be envisaged to skip the removal of damaged area in some cases such as spalling and directly spray the repair, which would lower the cost and time significantly. Another important challenge is exporting the in-lab repair process to field reparation. While the process in itself should not be difficult to implement, the gas and power supply must be taken care of. Moreover, the final heat treatment selected to this day implies high temperatures, which is not optimum for field repair. While solutions, such as induction heating can handle this kind of treatment, lowering the time and temperature of the post treatment could ease the implementation of in-field cold spray process. The process itself could still be improved to increase even further the efficiency of the deposit.

Deliverable(s): D4.4

36 Discrete defect repair of rail

Mike Poulter, *Network Rail*

Background

Complex interactions between the wheel and rail can lead to discrete defects developing on the rail head. Although it is possible to detect these defects using advanced monitoring technologies, current repair techniques (i.e., in-situ repairs including manual metal arc welding processes, thermite head repair processes or rail replacement) can be inefficient, weather dependent which can lead to acceptably high failure rates within the first 12 months. Many thousands of discrete defect repairs are carried out every year in Network Rail's track.

There is a need to develop a new solution to automate the discrete defect repair process to reduce maintenance times, increase productivity, ensure repeatable high quality, right-first-time repairs, whilst providing a safe, weatherproof solution that is much less reliant on the skills of the welding operator.

The Discrete Defect Repair (DDR) process is an innovative low preheat automated process for the repair of discrete defects on rails. Development to TRL5 in In2Track2 proved the metallurgical integrity of the automated process that mills a standard cavity in the rail to remove a defect, then repair welds the cavity using a flux cored arc welding process. A milling machine then reprofiles the repair to match the profile of the rail either side of the repair.

The objective of the proposed work in In2Track3 was to continue development of the Discrete Defect Repair (DDR) machine, to achieve full automation of the repair process and the demonstration of the proposed system of delivery to the repair site, including downloading and uploading of the unit.

Increased knowledge and implementable results

The DDR machine has developed successfully in In2Track3 to achieve the target of TRL7

Automation has been added to standardise every aspect of the DDR process from excavation and weld repair to reprofiling. Application of clamps, heaters and temperature sensors have been automated to eliminate process variability. Wire straightening and snipping to length is automated to occur ahead of every weld bead deposit, this provides consistent wire shape and length at the start of every weld repair. Higher resolution laser profile measurement has been added and the software has been developed to automate all the modifications.

The safety and robustness of the machine has been addressed by installing machine guarding with flash protected glass windows, cable protection, brakes, fume extraction, swarf recovery and a rugged control pad.

A DDR delivery to site solution has been developed and demonstrated using a crane mounted on a road rail vehicle to down / upload the DDR to track. Modifications have been designed to automate the downloading operation by using hoists incorporated into the DDR service skid to eliminate the crane and thereby enable use under overhead wires.

Trials have been carried out to extend the sections and grades that can be repaired. Rail grades R200, R220, R260 in 56E1, 60E2 and similar predecessor sections have been repaired. HP335 grade has been repaired and metallurgical results are excellent.

The DDR machine is CE marked, and an equipment manual has been produced. A Weld Procedural Specification has been approved by an independent European Welding Engineer. A HAZID was produced and mitigations implemented. Network Rail Acceptance Panel has confirmed that the introduction of trial DDR repairs is not a significant change to the railway. The DDR has received trial approval for restricted installation and monitoring in Network Rail track.

Repair welds were made on a heritage railway in early 2023 and the first Network Rail repair of a 75mm long wheel burn was made on 5th December 2023.

Implementation and open questions

The next steps in the DDR development is the trial installation of 50 DDR repairs in track. The trials will help to identify improvement opportunities to the DDR machine and to the installation process that will then be addressed by designing a version 2 DDR machine ready for commercial exploitation. Design work has already been carried out to address lower sector gauge infringements to enable use in third and fourth rail areas.

A concept design to incorporate the DDR into the maintenance management train is under development. This could facilitate a new defect management strategy based on early repair of rail head defects in a long-term maintenance plan (rather than the current approach of allowing defects to grow to 10mm deep before initiating a repair).

The DDR repairs will be monitored over the first year to capture evidence about the reliability, to compared to existing defect repair methods. FMEA and RAMS data will be gathered and used to support an application for full product acceptance by the end of 2024.

Further development of the DDR will be made to eliminate restrictions on where the DDR can be used. This will include automation of the downloading system to eliminate restrictions under overhead lines.

Deliverable(s): D4.4

37 Improved welding techniques

Magnus Ekh, Johan Ahlström, Björn Andersson, *Chalmers University of Technology / Trafikverket*

Background

Rails are made from high carbon steel to withstand the high stresses and provide sufficient wear resistance at a reasonable cost. However, this type of material can harden and become brittle during the welding process. Therefore, rail welding is challenging and requires careful selection of filler material, preheating (especially at colder temperatures) and other precautions. Instructions for welding are regulated, but as time for track maintenance is more and more limited, optimised procedures are required. As a tool for optimising the procedures, Computational Welding Mechanics (CWM) simulations can be used to predict the final weld properties and weld residual stresses for given process parameters. CWM simulations are developed and conducted in this chapter. This chapter also explores how CWM simulations can be employed as an assessment tool of welding techniques, that can provide a basis for improving current and future regulations.

Increased knowledge and implementable results

Macroscopic modelling of phase transformations and cyclic mechanical behaviour of low alloy steels has been developed and investigated. This modelling is required to predict which phases of the steel that are present during and after a welding process (or any other heat treatment process) as well as to predict mechanical stress–strain fields (e.g. residual stresses) and how they develop with heating and rolling contact loading. The importance of including transformation induced plasticity in the modelling has been analysed, as well as the choice of homogenisation technique in modelling the multi-phase material during heating and cooling.

The challenge of the long computational time associated with full-scale 3D multi-pass welding simulations is addressed by exploring different model reduction schemes. A 2D generalised plane strain model, extended with out-of-plane axial and bending stiffness, is found to replicate the full-scale model at a mere fraction of the computational cost. This makes it feasible to use simulations for analysing and assessing different welding process parameters.

The models and simulation methodology have been validated against experimental results from Jun et al. (2017) by comparing the longitudinal residual stress distribution in a welded rail cross-section.

A process parameter study has been carried out, see figure 37-1. The left column shows the results when only the top rail surface is preheated as in the experiment by Jun et al. (2017), the middle column when the entire cross-section is preheated and the right column when the last layer is applied using 3 times higher power than for the other layers. It can be concluded that the choice to use a higher power in the last layer influences the resulting material phases and residual stresses significantly. It results in a material with lower hardness and lower residual stresses close to the rail surface.

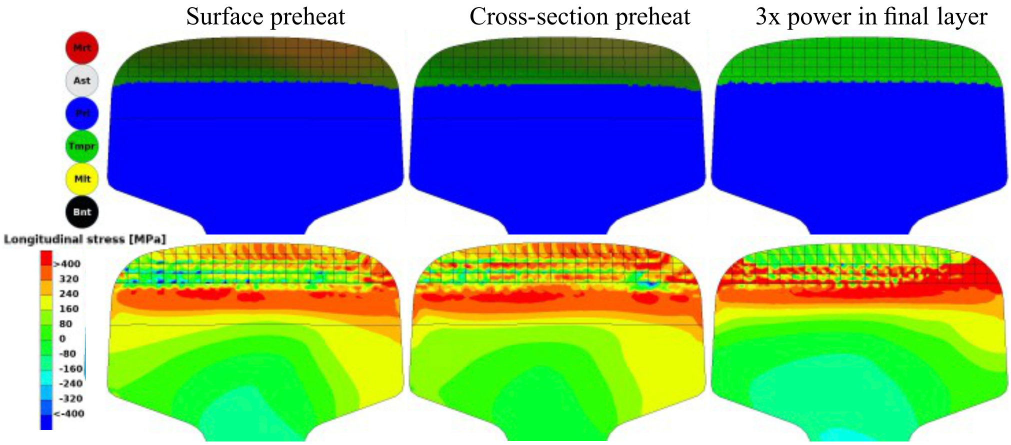


Figure 37-1 Variation of welding process parameters. Upper row: phase fractions (red: martensite, white: austenite, blue: pearlite, green: tempered martensite and/or bainite, yellow: melt and black: bainite) and lower row: longitudinal residual stress fields

Implementation and open questions

The simulation methodology includes models based on experimental data, such as phase transformation diagrams, dilatation curves, and temperature-dependent cyclic stress-strain responses. However, some of this data are estimated using Jmatpro software, and literature sources. To improve the reliability and accuracy of the methodology, it would be valuable to conduct well-controlled experiments and use this data to calibrate and validate the corresponding models.

The presented results also show that existing welding techniques can be improved by e.g. careful adjustment of operating temperature and heat input. This study is currently ongoing and will be continued by analysing results of various process parameters whereby improved welding techniques can be suggested. The proposed simulation methodology can be used to assess current welding regulations to provide a better understanding of their implications. By adjusting and optimising process parameters in the simulation methodology, future welding regulations can be suggested. This can significantly reduce the number of experimental investigations required before implementation of innovative welding processes.

Deliverable(s): D3.3

38 Track information model

Karrar Ibrahim, *Trafikverket*

Background

A blueprint, known as a "Reference facility" for designing a railway, as envisioned by the Swedish Transport Administration (Trafikverket) in their "Virtual Master Facility" study is tested. The goal was to see if Trafikverket's theoretical methods would actually work when applied to the real world.

A virtual 3D model of a railway facility was designed. This is more than just a digital lookalike—it's a layered digital model infused with in-depth data about the facility. Each layer gives insights into different aspects of the railway, from overall systems to individual parts and how they fit together.

The focus was on creating a digital version of the "Railway Track Structure." Imagine this as an interactive, computerised map of the tracks that can be analysed in detail. Using special software, we could interact with this model in three dimensions and tap into a wealth of stored information that are directly embedded in the 3D model or linked from external sources like asset management systems or databases. This setup made it simple to get detailed reports on various parts of the railway, helpful for maintenance and improvement strategies.

A critical part of the model was integrating the "TRVINFRA" regulations—Trafikverket's guidelines for railway design and maintenance. These rules were linked to different sections of the virtual model to understand the effects of changes in one area on the other. Through this approach, a digital environment was crafted where one could virtually explore a railway system, ensuring every part was examined and met the official standards. It was a step beyond simple modelling, creating an interactive tool that puts a wealth of information at our fingertips, all within the framework of established regulations.

Increased knowledge and implementable results

Creating a digital model for a railway facility shed light on the nuanced challenge of simulating a complex, real-world system. The task underscored the need for precision in representing the layers of physical components, operational functions, and regulatory guidelines that maintain the integrity and safety of railway infrastructure.

The project broadened the understanding of data management. Implementing the ISO standard 12006-2 was a lesson in categorising vast information systematically, ensuring that the digital structure was a faithful and navigable reflection of the real railway facility.

Incorporating BIMQ into the workflow was pivotal. This platform facilitated the detailed cataloguing of railway components, yielding a database rich in detail yet streamlined for practical use. Selecting appropriate design tools was another crucial step, leading to a setup that could handle real-time updates and create a living model of the railway that could adapt as real-world changes occurred.

Ensuring that every digital element mirrored real-world counterparts, the model was aligned with industry norms through the CoClass system. This alignment helped streamline the model's integration into existing industry processes and made the project's findings more accessible to stakeholders.

The advancement in semantic information modelling stood out as a key achievement. This approach enabled the clear definition and interrelation of railway components, bridging the gap between complex information and its practical application. It was essential for assuring that the digital model complied with the myriad of standards and regulations that govern railway operations. The effort extended beyond constructing a mere digital representation; it was about establishing a blueprint that could evolve. This living digital document captures the complete essence of a railway facility, accommodating updates, facilitating maintenance, and conforming to regulatory demands.

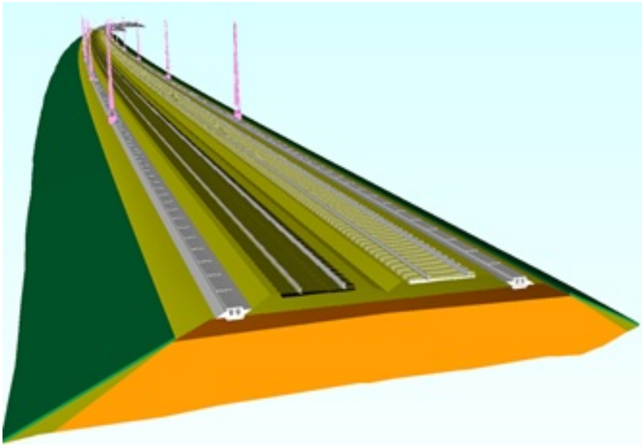


Figure 38-11 The resulting digital representation of a Railway Track Structure

In all, the exercise was more than technical—it was a strategic endeavour that enhanced the understanding of digital modelling in the context of infrastructure management. It demonstrated the potential of digital tools to not only replicate physical entities but to also serve as a foundation for future planning, analysis, and optimisation of railway systems.

Implementation and open questions

Semantic information modelling for railways is still novel in the EU. The application, poised to reach technology readiness level 6 (TRL 6), visually represents a railway track and regulatory details in 3D. The pilots conducted by Trafikverket are instrumental for this advancement.

The next stage is spearheaded by Trafikverket and SWECO AB, who are pushing the technology towards TRL 9 with a web-based application slated for completion 2025. This is a progression from the current project and will be implemented into everyday railway maintenance.

Additionally, a wider Trafikverket project is underway, applying the research to define the infrastructure elements. The goal is to integrate these tools into standard railway operations, testing them extensively for practicality and scalability. As the research unfolds into application, it's expected to reveal new challenges and questions, which will inform the direction of subsequent innovation and research in railway system management.

Deliverable(s): D3.4

39 Evolution and degradation of a ground rail in a digital twin

Caroline Ansin, Fredrik Larsson, *Chalmers University of Technology / Trafikverket*

Background

In curved railway tracks, the contact between wheel and rail often results in high tangential contact forces which can cause damage to the rails such as material being worn off from the surface (wear), redistribution of material (plastic deformation) or crack initiation and propagation caused by Rolling Contact Fatigue (RCF). Rail damage can eventually lead to rail failure if not mitigated in time. This can result in traffic interruptions or train delays. Therefore, the rail must be maintained, resulting in frequent physical inspections, grinding, or installation of new rails which is associated with high costs. Numerical simulations in combination with field measurements offer a promising approach to predict rail damage, which can be used for optimisation of maintenance procedures.

Increased knowledge and implementable results

In this work, we have implemented a digital twin being a numerical model mirroring its physical counterpart, the rail head. It provides accurate predictions of rail damage through fast and memory-efficient simulations, surpassing real-time occurrences. The digital twin's accuracy is continually improved and validated through updates facilitated by field measurements, as can illustrated in figure 39-1. This is crucial for optimising maintenance timing and action.

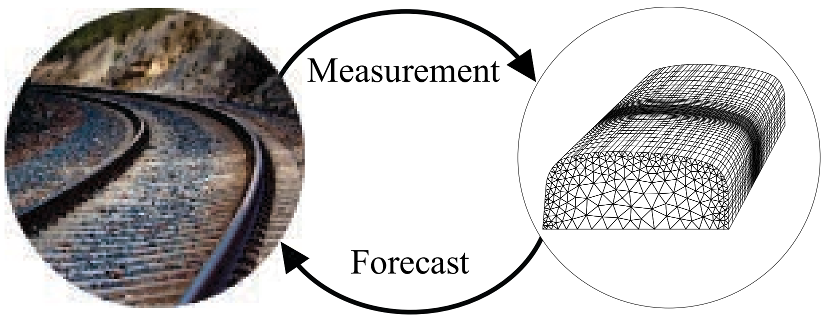


Figure 39-1 In a digital twin framework, the numerical model is continuously being updated by field measurements to improve the accuracy of the predictions of the material damage in the rail head.

The digital twin predicts the evolution of rail cross-sections over time. This is done through feedback loops involving dynamic vehicle-track interaction, elastic-plastic wheel-rail contact, and the accumulative rail damage attributed to plasticity and surface wear to update the rail profile, as well as the initiation of cracks. Incorporating field measurements in these feedback loops allows for effective calibration of the model parameters. Validation is also ensured through comparing simulation results to experimental field data, i.e., assessing the accuracy of the calibrated digital twin.

Two studies were conducted to analyse the digital twin. The first study compared predicted profile changes to field measurements under estimated operational conditions. A few sections along the Western main line in Sweden were studied, with known traffic load and measured development of rail profile geometries. This enabled model calibration for average geometry changes. Calibrating these average geometry changes allows for better predictions of future damage to the rails. Also, crack initiation and formation were investigated, which gave an insight to where on the rail profile cracks initiate and for how much traffic In the second study, an analysis of wear distribution on rail profiles was undertaken to assess the impact of various model parameters. Inclusion of freight vehicles in the traffic mix, and the utilization of a varied set of measured wheel profiles in the simulation framework showed promising results when it came to a more spread out wear distribution, which is more similar to what is seen in the measurements

To improve numerical efficiency, a reduced-order model was developed, for accurate simulations of rail deformation under varying contact loads. This model is important for conducting cost-efficient simulations within the digital twin framework, particularly important when managing high volumes of traffic.

Implementation and open questions

The existing framework serves as a comprehensive tool for simulating the degradation of a rail within a digital twin framework. It has been demonstrated that the simulation tool can be calibrated to fit field measurements of the average geometry changes and which model parameters are influential to the wear distribution of the rail profile.

To enhance computational efficiency further, the reduced-order model will be expanded to accommodate an elastic-plastic material response in the rail so it can be incorporated in the digital twin framework. In addition to continuous and upcoming model developments, the subsequent stages include the extended calibration of the model using a longer series of measurements. This process aims to evaluate the model's potential as a long-term "digital twin."

Deliverable(s): D3.4

WHEEL / RAIL INTERACTION

40 Improved ride comfort by development of a new indicator

Matthias. Asplund, Martin Li, *Trafikverket*, Pär Söderström, *SJ*, Ingemar Persson, *DEsolver,* Lars-Ove Jönsson, *Analytical Dynamics*, Mats Berg, *Royal Institute of Technology*

Background

Ride comfort is a product of the infrastructure and rolling stock, both must be in good condition to obtain a good result. In other words, they need to perform well together to obtain the final product of good ride comfort. Good ride comfort is a prominent issue for the credibility of railway transports. Besides reducing the appeal of rail transport, poor ride comfort also inhibits the capacity on the track by speed restrictions and leads to loss of punctuality due to the impact on the train table. On a higher level, good ride comfort supports the shift to more green transport modes and sustainable transport solutions, this by enhancing the capacity and by that improving the attractiveness of the railway.

The equivalent conicity in the wheel-rail contact has a high influence on the ride comfort. But since equivalent conicity is the result of the combination of wheel and rail profiles there are presently no reliable metrics that can assess the performance of wheels and rails independently. The current work has defined new indices that can be used to judge the wheel and rail profiles in combination, as well as separately, to keep high passenger comfort on passenger trains.

Increased knowledge and implementable results

The idea is to compare the inclinations (gradients) of the wheel and rail profiles at the nominal contact point on tangent track. See figure 40-1 and equations 40-1 and 40-2. The quantities are called Gradient Index Profile, GIP.

$$GIPw = 100 \cdot \frac{dZw}{dYw}\ ; \quad GIPr = 100 \cdot \frac{dZr}{dYr} \qquad (Eq\ 40\text{-}1)$$

$$GIP = \frac{GIPwL - GIPrL}{GIPwL + GIPrL} + \frac{GIPwR - GIPrR}{GIPwR + GIPrR} \qquad (Eq\ 40\text{-}2)$$

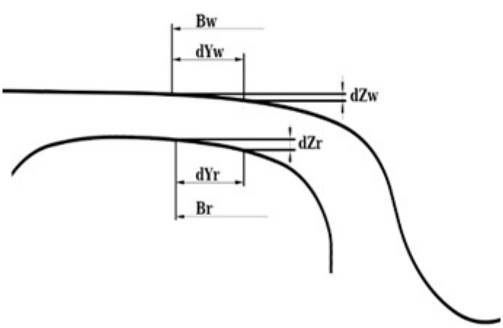


Figure 40-1 The geometrical definition of GIPw and GIPr

The definitions can be found in Table 40.1. The inclination of the wheel is GIPw (w=wheel), and the inclination of the rail is GIPr (r=rail). The indexes are calculated for left and right side separately, and then combined to the GIP index, which essentially is the difference in gradient between wheel and rail.

This parameter has a good correlation with the equivalent conicity but has the added benefit that wheel and rail can be assessed separately, which the equivalent conicity cannot do.

Table 40-1 Definitions of parameters according to the figure and equations above

Parameter	Definition
GIPw	GIP for wheel, GIPwL and GIPwR, left and right side respectively
GIPr	GIP for rail, GIPrL and GIPrR, left and right side respectively
GIP	GIP combined, a combination of the four values above (wheel and rail, left and right)
Bw	= 750 mm, the lateral distance of the reference point from centre of wheelset
dYw	= 15 mm, for finding the vertical position to determine dZw
Br	= 751 mm, the lateral distance of the reference point from centre of track
dYr	= 16 mm, for finding the vertical position to determine dZr

Calculations of the GIPr has been performed to a track section of 455 km ballasted double track between Stockholm and Göteborg in Sweden. The track has a maximum speed of 200 km/h and a maximum axel load of 22.5 ton. In this investigation only tangent track has been considered. Figure 40-2 shows the track section that has been investigated.

Figure 40-2 The track section in the south of Sweden between Stockholm and Göteborg that has been evaluated with GIPr

Implementation and open questions

The results of the GIPr analysis is presented in 40-3, where a 2D histogram shows the distribution of equivalent conicity versus GIPr, with the conicity calculated with a worn reference wheel profile. A total number of 178 516 pairs of measured rail profiles are included. The figure also shows the proposed Intervention Limit (IL) and Alert Limit (AL), where the proposed limits are GIPr IL = 6.5 and GIPr AL = 8.0.

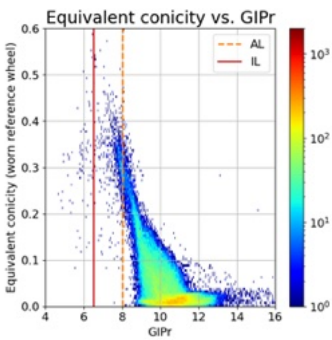


Figure 40-3 Equivalent conicity vs. GIPr

The GIP index is included in the technical report CEN/TR 17792:2022, and the GIP index has also been presented at several international conferences. Currently GIP is implemented by the infrastructure manager Trafikverket with the goal of assessing the rail profiles in terms of comfort performance on tracks with maximum speed of 200 km/h and above. The GIPr will be used as an indicator of when reprofiling is needed to keep a good performance with respect to passenger comfort. Also, the wheel profile measurement system that are installed on the infrastructure to measure all wheels that pass the checkpoint will be evaluate all wheels with the GIPw value. These above-mentioned implementations will improve the comfort and enhance the credibility of railway transports on track to support the shift to more environmentally friendly transports.

Deliverable(s): D3.4

41 Condition monitoring of vehicle running stability

Rohan R Kulkarni, Alireza Qazizadeh, Mats Berg, *Royal Institute of Technology*

Background

The dynamic interaction of rail vehicles running along the track is crucial for the system performance in terms of safety, wheel and rail maintenance, ride comfort and running stability. Condition monitoring of this interaction throughout the system life has therefore become more and more important, traditionally via sensors in the track but in recent years also via sensors onboard the vehicles.

The present work has focused on onboard condition monitoring of vehicle running stability. Possible running instability, describing a lateral oscillation of the vehicle in the track, is a system malfunction that often originates from poor wheel-rail interfaces including the track gauge (distance between the two rails) being a bit tighter than nominal. This instability may occur as the vehicle is running at fairly high speed on straight track or in large-radius curves.

A key issue in this context is the development of a proper indicator for detecting vehicle running instability and, in particular, a root cause identifier so that proper system actions can be taken to resolve the instability. This calls for some kind of algorithm that can boil down extensive onboard sensor data from in-service vehicles to indicators and identifiers. An important tool in this process is to make use of machine learning, now becoming powerful also in the railway sector.

Increased knowledge and implementable results

In the present work, KTH has collaborated with mainly Trafikverket and SJ (the main passenger train operator in Sweden). Since a few years SJ has instrumented the X2000 train fleet with accelerometer sensors, mainly on the axle boxes but some also in the car bodies. Extensive acceleration (vibration) data from several X2000 trains and vehicles as they operate on Swedish railway mainlines has been used, but initially also corresponding simulations to try out different algorithms.

One key observation in the work is that running instability is an anomaly (only occurs now and then), and that this needs to be reflected in the present development of indicators and identifiers. Another observation is that vehicles run unstably only on some track sections and that on the same track sections other vehicles of the fleet do not experience any running instability. This calls for a broader and more challenging perspective on the task at hand.

In the figure below a framework of the present methodology, called iVRIDA-fleet, is illustrated. It has primarily been applied to the X2000 train fleet as it operates on the Swedish railway mainlines. The present work has focused on the "four boxes" to the right in the figure. Note the three different clusters (root causes) in the upper left box in the fault identification (VFI) process. The present indicator of running instability works well whereas the root cause identifier needs some further development.

Implementation and open questions

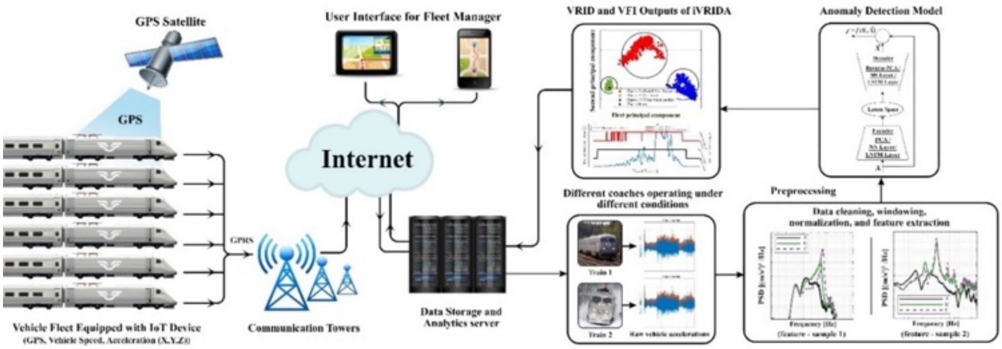


Figure 41-1 Intelligent Vehicle Running Instability Detection Algorithm (iVRIDA-fleet) Framework for X2000 fleet.

The above methodology (scheme) has partly been implemented, but some further refinement is needed together with practical tasks linked to how the fleet is operated and how vehicles and tracks are maintained. A challenge is also how all stakeholders can cooperate and communicate in the best way so that a detected vehicle running instability can be quickly resolved by proper vehicle and/or track maintenance actions. This also means that the running instability should only cause a minor disturbance to the regular train traffic and the passenger vibration comfort.

The Royal Institute of Technology is, together with railway stakeholders, planning to continue the work summarised above.

Deliverable(s): D3.4

42 Stable wheel and rail profiles over time

Elham Khoramzad, Saeed Hossein-Nia, Mats Berg, *Royal Institute of Technology / Trafikverket*

Background

The shapes of wheel and rail profiles are evolving over time due to the wheel-rail contacts and associated forces and sliding motions resulting in wear. Ideally the nominal (initial) profiles do not wear much, and the still existing wear is fairly well distributed across the profiles so that the profile shapes do not alter much during the operation. In this way a vehicle–track system, initially optimised with respect to dynamic performance, would have a low deterioration rate giving better ride comfort, less running instability and reduced maintenance costs. However, the choice of such initial profiles is challenging due to mixed operational conditions including for instance different vehicle types on the same railway line and different railway lines operated by the same vehicle type. Wheel reprofiling and rail grinding/milling do also "interfere" with the "natural" wheel-rail contacts.

In the present work, carried out in collaboration with Trafikverket and SJ et al., the focus was on the choice of initial (nominal) wheel profile but acknowledging the importance of the rail profiles and other track geometry properties. The choice of initial wheel profile is crucial for the vehicle–track interaction and in particular the wheel–rail interaction. The choice has significant influence on safety aspects, running stability, ride comfort, wheel and rail damage as well as maintenance costs.

Globally and through the years, many wheel profiles have been suggested and implemented depending on application but also tradition. Usually vehicle design, payload, top speed, track design geometry and rail profile will influence the choice of wheel profile. As indicated, a further challenge is that the wheel (and rail) profile will change over time due to wear in the wheel-rail contact at different operational conditions. This could mean that an initial wheel profile works well, but the worn profile after say 200 000 km might not.

Increased knowledge and implementable results

In the present work, a new wheel profile has been proposed mainly intended for X2000 coaches running on the Swedish railway mainlines. The profile, called ENX2, is derived by combining measured wheel tread profiles of X2000 coaches and the nominal S1002 wheel flange (flange thickness 31 mm). The measured profiles refer to wheels that have run for about 100 000 km, which roughly corresponds to halfway before wheel reprofiling. See figure below.

The goal has been to come up with an initial wheel profile that can last for longer running distance before reprofiling as compared to the S1002 profile used today in X2000 coaches. To evaluate the potential of the proposed ENX2 wheel profile, extensive simulations have been carried out and compared with the S1002 profile. In this context, the two initial profiles have been compared with respect to wheel–rail forces at curve negotiation and running stability on straight track.

Giving promising results, extensive wheel wear simulations have been done following the methodology KTH has been working on for many years. Again, both profiles have been studied and the worn S1002 profiles validated against measured worn profiles. For worn ENX2 and S1002 profiles, after 200 000 km (see figure 42-1), dynamics evaluations are carried out once more.

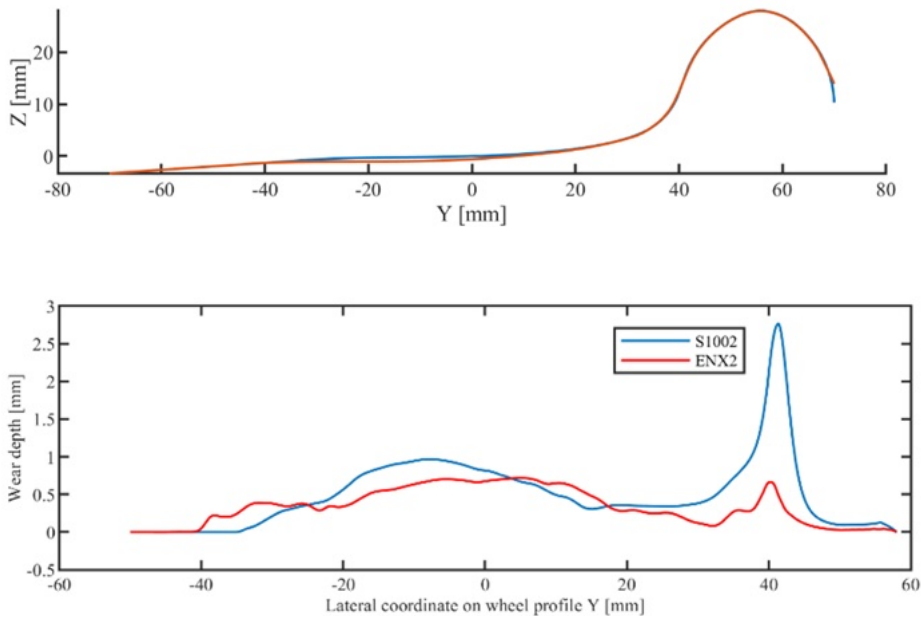


Figure 42-1 Initial wheel profiles of S1002 and ENX2 (top). Simulated wear depth of S1002 and ENX2 for outer axles after 200 000 km of running distance (bottom).

From the simulations it is concluded that the proposed ENX2 wheel profile works well with respect to safety and running stability as well as ride comfort, and in most studied cases outperforms the S1002 profile. Thus, ENX2 is promising from both vehicle–track dynamics and wear perspectives and has the potential of extended running distance before reprofiling.

Implementation and open questions

Although there are some concerns on the running stability and so-called equivalent conicity, long-term field tests should be carried out for some X2000 coaches with ENX2 profiles and, for the same operational conditions, compared with S1002 profiles. However, this is beyond the In2Track3 project and depending on a decision by SJ and Trafikverket. It should also be noted that a possible success with ENX2 also depends on how the rail profiles develop (design profile, wear/RCF, grinding/milling). Thus, the evolution of rail profiles in different curves should also be studied.

Deliverable(s): D3.4

43 Impact of rail steel grade on rolling contact fatigue

Urs Schönholzer, *SBB CFF FFS*

Background

There are several different types of steel alloys in use for the manufacture of rails. The most common of these so-called steel grades can be divided into two main categories: normal and head-hardened steels. The selection of the appropriate steel grade is not an easy one. Unfortunately, the hardening process that improves the resistance of the rail head has not only advantages. The International Union of Railways (UIC) publishes guidelines for the selection of steel grades depending on traffic and on the local radius of curvature. These guidelines have been initially published in 2005 and were revised in 2015. SBB and other rail infrastructure managers has internal regulations on the use of rail steel grades derived from UIC's suggestions. The goal of this work was to see if an adaption in the selection criteria can lead to an optimised application of the steel grades with a potential for cost reduction by avoiding the generation of rail defects.

The method we used was an analysis of a dataset containing more than 18'000 rail defects that have been found in SBB's rail network by ultrasonic testing (UT) in the years 2015 to 2022. Each of these defects cost in the order of 6,000 to 8,000 € to fix. Therefore, the improvement of rail grade selection criteria with the goal of reducing the overall number of defects is important also of interest from a financial standpoint.

Increased knowledge and implementable results

We took the basic dataset of the UT defects and added meaningful context from other sources, such as track geometry data and the traffic load. Traffic is measured in tonnes per day (combined weight of all trains on the respective section of track in one calendar day) and cumulated track load over the lifespan of the rail in million gross tonnes (MGT).

All possible rail defect types were aggregated into three classes for the analysis. The most frequent defect type is the so-called squat (approx. 13'000 defects), the second distinct defect is the head check (approx. 2'000 defects). All other defect types combined were put into a single class (approx. 3'500 defects). These figures contain defects from plain line as well as from switches.

For the main part of the investigation, only data from UT defects on open lines is investigated. In addition, only steel grades and rail profiles currently purchased by SBB are considered, data from legacy steel grades still present in the network has been discarded. Steel grades that were investigated are R260 as standard rail grade and R350HT as head-hardened type. A constraint for the actual dataset used in the analysis was the availability of data for both the radius of curvature of the respective track section, and of data about the traffic load. These parameters had to be taken from different databases and needed to be matched to the exact location of the UT defect. Merging the data from different sources was lossy because of past changes in unique identifiers for some track sections. The annual track load for the year 2021 was applied to calculate the cumulative load over the lifespan of the rails in million gross tonnes (MGT). This probably overestimates the load for older rails by a low double-digit percentage value, as traffic increased over the years. The data in figure 43-1 shows the final result of the analysis of defect distribution depending on the daily traffic load and on the radius of curvature of the respective track.

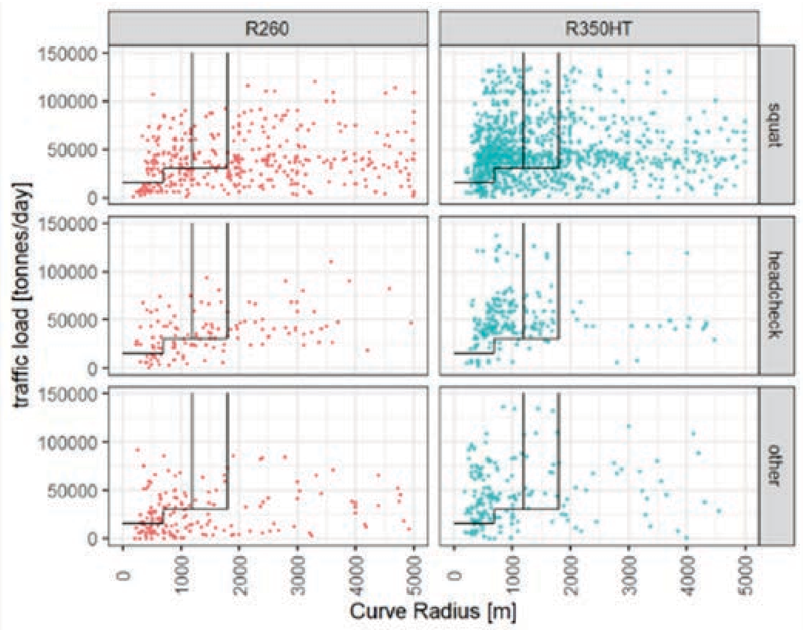


Figure 43-1 UT defects, depending on load per day and radius. The black lines correspond to the steel usage chart currently in use. N ≈ 3000

In the particular area of interest with curve radii in the range of 800 to 2000 m, no clear pattern has been found that would lead to a change in steel grade selection. Therefore, the current method will be maintained. There was, however, a clear indication that head hardened steel should not be used in tangent track, as the lifespan is about half of the normal steel grade for this application. This is in alignment with observations from other railway infrastructure managers.

Implementation and open questions

The results are based on a significant statistical basis and are therefore considered mature. Based on the outcome, SBB are not going to adapt the internal steel grade usage recommendations, as there has been no factor identified that can easily reduce life cycle cost by changing the rail placement strategy depending on traffic load and radius of curvature. We will, however, continue the investigation. The results presented here may have a bias, as only rails with UT defects have been part of the dataset. For a next step, we would like to relate rails that develop UT defects under a given set of factors considered in this study, to rails with comparable factors that do not develop defects. We expect this additional analysis leads to additional insights on the behaviour of the different rail steel grades. This could help us to reduce the squat defects occurring in our network and therefore reduce maintenance cost for rail replacements.

Deliverable(s): D3.1

44 Influence of wheel tread characteristics on operational lives of rail and running gear

Michele Maglio, Elena Kabo, Jens Nielsen, Tore Vernersson, Anders Ekberg, *Chalmers University of Technology / Trafikverket*

Background

Have you ever heard a repetitive (and maybe annoying) noise, something like a rhythmic "thump thump thump thump", while travelling on a train or on a city tram? Then the vehicle you were travelling on might have been affected by a wheel flat.

Wheel flats are just one of many possible defects which can occur on the wheel tread, the surface of the wheel which is in contact with the rail. Wheel flats can form when the train is running with a frozen brake that causes the wheel to slide on the rail. They are therefore not uncommon in the Swedish railway system during winter-time.

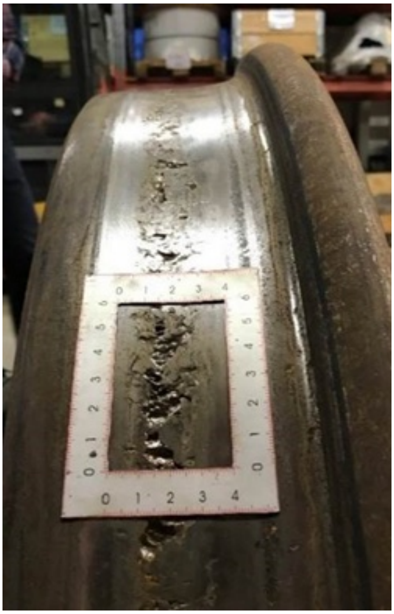


Figure 44-1 Wheel with severe rolling contact fatigue damage

Another commonly occurring form of tread damage is surface cracking that may form clusters. An example of a railway wheel with a severe form of such a rolling contact fatigue crack cluster can be seen in figure 41-1. Contact forces between the wheel and the rail, in particular high tangential forces, can cause these forms of damage.

Wheel tread damage leads to high magnitudes of vertical wheel–rail contact forces. Vehicles generating wheel–rail impact loads exceeding set limit values must be taken out of service for wheel maintenance. This may lead to severe traffic disruptions and associated high costs. In addition, increased wheel–rail impact loads cause elevated stress levels in wheels, axles and bearings and may shorten the life of track components, resulting in higher costs for vehicle and track maintenance. Thus, alarm limits should provide a balance between preventing operational failures and minimising the number of stopped trains.

Increased knowledge and implementable results

Field tests to assess the influence of wheel tread damage on vehicle and track loading are expensive and difficult to arrange. Instead, a versatile and cost-efficient method to simulate the vertical dynamic interaction between a wheelset and a railway track, accounting for generic distributions and shapes of wheel tread damage has been extended and improved. The dynamic coupling between the two contact points (one on each wheel) via the wheelset axle and via the rails and sleepers is accounted for. Post-processing steps to evaluate fatigue impact at critical positions in the wheelset have been developed.

The employed simulation models have been calibrated and verified by extensive field tests with two different Swedish passenger trains. In the first field test, impact loads generated by a wheelset with severe tread damage were measured in one of Trafikverket´s track-side wheel impact load detectors. Measurements and simulations have been used to illustrate how wheel–rail contact loads and fatigue impact depend on the three-dimensional shape of the tread damage. The effects of speed and travelling direction of the vehicle, position in the sleeper bay where the defect strikes the rail, lateral wheel–rail contact position relative to the tread damage, and track stiffness on wheel–rail contact forces and wheelset durability have been investigated. For a given wheel tread damage, it was found that an increase in train speed can lead to a substantial increase in wheel–rail impact load, while the influence on bending stresses in the wheelset was not as pronounced.

In the second long-term field test, axle strains were monitored using an instrumented wheelset on a passenger train in revenue traffic. Based on post-processing of test results, statistical models of stress spectra for different stretches of the Swedish rail network were obtained. Moreover, the parameters describing such models have been related to track characteristics in terms of the presence of curves, switches & crossings and irregularities in track geometry. This allowed to develop numerical routines to evaluate wheelset durability depending on operational parameters. These studies have been used to initiate a discussion on improved wheelset maintenance procedures as well as to provide an objective categorisation of track section quality. The results of these studies will contribute to improved regulations and maintenance practices for wheels with tread defects.

Implementation and open questions

The implementation of the simulation model in the in-house software WERAN can be used to establish fatigue-stress spectra for different designs of the running gear, track characteristics and wheel tread damage. This should be useful for future wheelset design. Efforts on the characterisation of wheel tread damage and coupling the defect geometry (e.g. depth and length) to operational parameters should continue. This would for example be of help in applying a speed restriction for a train with a detected severe wheel tread damage. Operation could then be carried out until maintenance is more cost-efficient, avoiding unnecessary stopping of trains without causing further damage to the track and running gear, and without jeopardizing safety.

Further studies may focus on the relationship between data collected from sensors (regardless of whether they are installed on the vehicle or in the track) and the presence of wheel tread damage and/or track irregularities. Time histories of signals collected in field can be integrated in calculation algorithms and digital twins. This would be of help for both the vehicle owner and track manager in maintenance planning, allowing to increase safety and punctuality while optimising resources.

Deliverable(s): D3.4

45 Brake rig testing of generation and evolution of wheel defects

Tore Vernersson and Eric Voortman Landström, *Chalmers University of Technology / Trafikverket*

Background

Mitigating wheel tread and railhead damage is a disrupting and costly wheelset maintenance action. Wheel tread damage is also a main cause for high wheel–rail contact forces that detrimentally contribute to degradation of both track and rolling stock components. To minimise unnecessary re-profiling while ensuring that wheel defects do not grow to unacceptable levels, it is vital to investigate how the defects initiate and grow under realistic and controlled conditions.

A novel full-scale brake roller test facility allows for study of thermally induced cracks, which is one of the worst forms since they can occur also on rather new wheels. The lab setting allows for wheel–rail contact conditions not present in traditional brake test rigs since these are usually made for standardised brake testing and homologation. The new test facility includes a tread braked wheel, tread brakes and a so-called rail–wheel in a rail module, see figure 45-1. Results can be employed to limit damage generation and optimise maintenance to limit detrimental influence on track while maximising fleet operations.

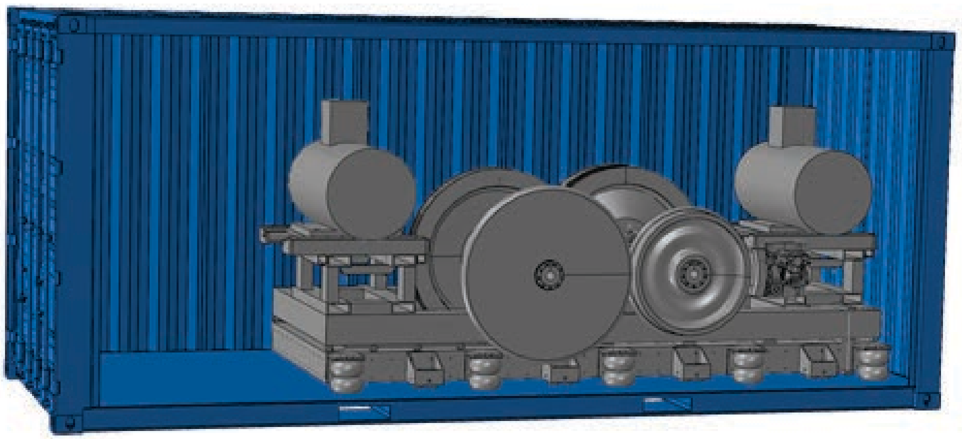


Figure 45-1 Novel full-scale brake roller test rig

Increased knowledge and implementable results

It has long been known that block (tread) brakes produce an uneven temperature field on wheel treads, where evenly spaced hot areas, so-called "hot spots", develop around the wheel tread circumference during prolonged braking. To investigate the impact of such localised heating phenomena on wheel performance in general and on wheel residual stresses in particular, a combination of experimental testing and finite element simulations of tread braked wheels were performed. Brake test rig results were coupled with numerical simulations to investigate the consequences of different types of temperature variations. In addition to this, a field test campaign was launched, partially financed by the Swedish iron ore company LKAB, to study temperature variations of wheels on wagons.

The experimental results from the brake test rig show that temperatures measured by sliding thermocouples provide insufficient information and had to be complemented by high-speed thermography. Non-uniform heating is found to have a significant effect on wheel tread plastic behaviour and tensile residual stresses in the rim. By use of 3D finite element simulations, it was shown that locally heated areas larger than some 60 mm had important effects on detrimental residual tensile stresses, whereas smaller ones (below some 30 mm) have a minor effect.

Global uneven temperatures with temperature differences over 200 °C between hot and cold zones on the wheel had a substantial impact on the wheel behaviour and can generate potentially hazardous residual stresses not found in wheels heated uniformly. Such a temperature difference has by numerical simulations in this project been found to represent a wheel out-of-roundness (OOR) of about 1 mm that is present during braking. This OOR could result in a substantial increase of wheel–rail contact forces, which has previously not been considered. This can have a considerable effect on wheel and track damage and degradation. Similar global uneven temperatures were found on wheels of wagons in operation on the Iron ore line, see 45-2, but the temperature differences are smaller and the phenomenon is less common than in the rig.

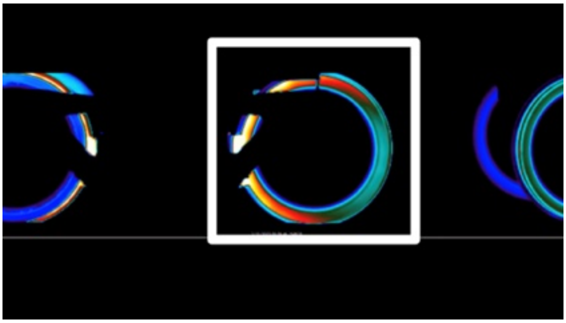


Figure 45-2 Uneven heating of an iron ore wagon wheel. Maximum difference 80°C on wheel rim front face of indicated wheel.

Implementation and open questions

The understanding, evaluation, and modelling of local and global uneven temperatures of wheels has taken major steps forward but is still in early stages. That is even more true regarding consequences in terms of wheel (and subsequently rail) deterioration where also factors such as the influence of crack growth directions and rates are investigated. Still, even these early results provide input to wheel design procedures (which thermal loading the wheel should sustain) and monitoring/maintenance procedures.

The observed temperature variations also have some implications for the wayside thermal warning systems currently in service, since these measure the wheel temperature at one spot on the rim only, which might not be representative for the entire wheel.

The results on global uneven temperatures of wheels are presently being investigated more thoroughly and it is premature at this stage to draw any general conclusions.

Deliverable(s): D3.4

46 Influence of out-of-round wheels on probability of rail breaks

Jens Nielsen, Anders Ekberg, *Chalmers University of Technology / Trafikverket*

Background

Severe wheel–rail impact loads generated by discrete wheel tread surface irregularities (e.g., wheel flats or material fall-out from clusters of rolling contact fatigue cracks) that increase the risk of rail breaks and may cause damage of track and vehicle components leading to high maintenance costs and traffic disruptions. Wheel impact load detectors (WILDs) are used to monitor vertical wheel–rail contact forces. Alarm limits for (maximum) wheel loads are prescribed to prevent wheel loads that may have safety implications. For example, the UIC recommended alarm limit for peak wheel load proclaims an immediate stop of the train at a wheel load of 350kN with an alert level at 300kN.

Increased knowledge and implementable results

A simulation-based methodology to evaluate the influence of a measured distribution of out-of-round wheel loads on the probability of a rail break has been developed. The simulation procedure includes applications of field test data, statistical analyses, and a validated model for simulation of vertical dynamic vehicle–track interaction. Meta-models are applied to reduce the computational cost of the analysis.

For predictions of high-magnitude impact loading in situations with potential loss of wheel–rail contact, simulations of dynamic vehicle–track interaction are carried out in the time domain using an in-house code to establish the resulting loading of the rail. A single gauge corner crack is considered. In general, this assumption of a single crack overestimates the crack loading. It should however be remembered that several nearby cracks may trigger multiple failures which has safety implications. A linear elastic fracture mechanics approach is employed to calculate the stress intensity at a deep rail head crack in a continuously welded rail subjected to combined bending and temperature loading. Based on eddy current measurements, the cumulative statistical distribution of rail head crack depths has been assessed for different curve radii intervals in a given track corridor on the heavy haul line Malmbanan.

The probability of the rare event of an instant rail break corresponds to the probability of an occurring situation where the impact load causes a maximum stress intensity at the pre-existing rail head crack that exceeds the fracture toughness. This can be illustrated by a performance function . Considering probability distributions of various stochastic variables, the probability of failure is determined as the probability of <0 (fail region). In the example in Fig. 4.1(a), it is observed that <0 only under very specific conditions. This is where the dynamic load and crack depth are near their maxima (and the rail fracture toughness is near its minimum).

To demonstrate the procedure, the probability of a rail break has been estimated for a scenario involving a freight traffic load spectrum measured in a WILD. Three stochastic variables were considered: wheel–rail dynamic load following a three-parameter Burr distribution that includes a representative contribution of high impact loads due to out-of-round wheels, crack depth with a statistical distribution based on eddy current measurements, and fracture toughness according to a normal (Gaussian) distribution. The risk of a rail break has been evaluated for four rail temperatures with values below the stress-free temperature of $\Delta T = 35$, 40, 45 and 50 °C, and for 10 different ballast/subgrade stiffnesses k_b (per half sleeper) in the interval 10 – 100 kN/mm.

The evaluated influence of ΔT and k_b on the risk of a rail break (probability of failure P_f) is summarised in figure 46-1 (left). As expected, the risk of a rail break increases with decreasing rail temperature (increasing ΔT) and decreasing ballast/subgrade stiffness. The label on the vertical axis in figure 46-1(right) should be interpreted as the predicted probability of an event leading to an instant rail break. For example, if it is assumed that each wheel (with radius R_w) generates one severe impact load per revolution, then the probability $P_f = 1\cdot10\text{-}7$ would correspond to one rail break in $D_w = 2\pi R_w/P_f \approx 28\,000$ km rolling distance for $R_w = 0.45$ m. For one freight train with N_w wheelsets, this would resemble a travelled distance of D_w/N_w if all wheels induce the same load.

Implementation and open questions

The simulation procedure provides a scientific foundation for improved regulations and management of wheel tread surface irregularities. For a given traffic scenario, and with measured distributions of dynamic loads and rail head crack depths, the approach could be applied to specify alarm limits in terms of maximum allowed peak load, as well as rail monitoring and maintenance strategies to ensure a specified highest risk of rail breaks. This would support cost-efficient, safe, and reliable railway operations with a minimum of traffic disruptions. Since different traffic scenarios can be compared, the feasibility of restricted operations (for example in terms of speed) can be studied. A fundamental understanding of the influence of wheel tread irregularities on the risk for crack growth and instant rail breaks is the scientific basis for optimising alarm limits even further.

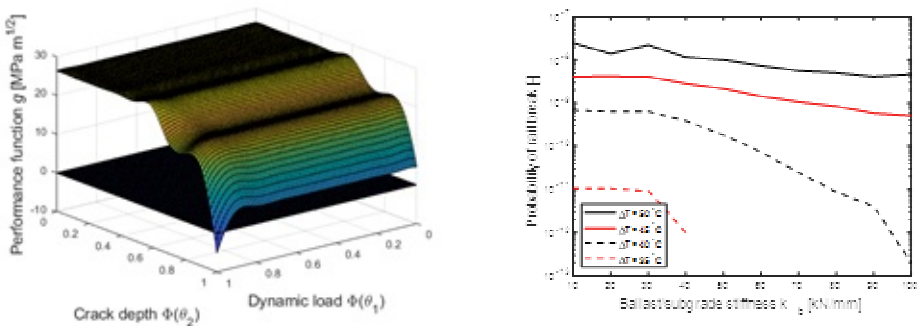


Figure 46-1 Left: Example of influence of cumulative distributions of crack depth and dynamic wheel load on performance function g, Right: Example of influences of ΔT and kb on probability of rail break. Freight traffic model with axle load 25 tonnes and train speed 100

Deliverable(s): D3.4

47 Performance of friction modifiers on track

Urs. Schönholzer, Franziska. Zbinden, *SBB CFF FFS*

Background

The aim of top of rail friction modifiers is to achieve optimal tribological conditions in the contact point of wheel and rail. The use of such products is part of a wider wheel and rail management strategy and must not compromise the safe operation of the railway.

A top of rail friction modifier is applied for various purposes such as

- minimising noise emissions and vibrations
- minimising rolling contact fatigue or the rate of wear
- minimising corrugation formation
- minimising energy consumption

Today, two main challenges hinder the wide use of top of rail friction modifiers in the interoperable European rail network. First is the difficulty of directly transferring the results obtained in the laboratory to a real railway system. For this reason, extensive on-track tests are necessary to assess the performance and to pass the approval process. The second is the lack of standardised methods to assess the performance of top of rail friction modifiers under operating conditions in track. Therefore, publicly available measuring results are not necessarily comparable and not transferrable from one network to another.

The objective of our work was to investigate the principal mechanism of friction modifier products under normal operating conditions in track and compare the field test results with results achieved in the laboratory. Two topics were of main interest: the influence of a top of rail friction modifier on the braking performance and on the lateral wheel-rail forces in narrow curves.

Increased knowledge and implementable results

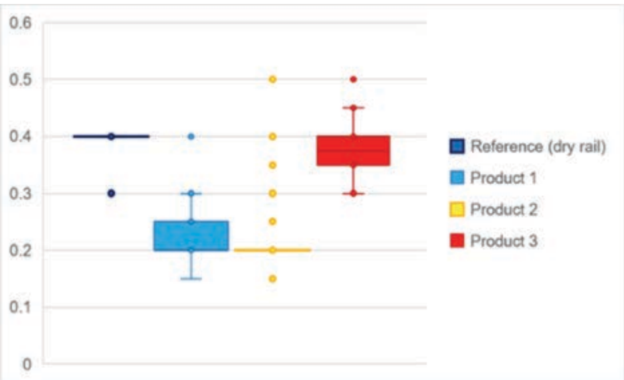


Figure 47-1 Static friction coefficient measured on the running band of the rail head

On-track tests assessing both the friction coefficient on the rail as well as the braking performance of different vehicles showed that the results for friction coefficient, braking performance as well as the adhesion coefficient are consistent both in the field as well as in the laboratory and confirm that the target range for the friction coefficient of 0.3–0.4 is suitable in order not to reduce the braking performance of running trains.

The results showed, that whenever the friction coefficient corresponded to the target range, the braking performance was not affected for speeds up to 120 km/h. When the friction coefficient was below the target range vehicles reacted differently based on their braking system: While no adverse effects on the braking performance of a tread-braked vehicle were observed, this was not the case for disc-braked vehicles. The braking performance of disc-braked vehicles was reduced and the wheel-slide protection system – which should be inactive under such conditions – had been activated in all cases.

Additionally, it could be shown, that the standardised measuring method defined in the UIC leaflet 544-1 is suitable to assess the braking performance of vehicles when applying a top of rail friction modifier and is therefore recommended for use.

Friction coefficient and lateral wheel-rail forces in narrow curves

Lateral wheel–rail forces were continuously measured with instrumented wheelsets in narrow curves with radii between 190 and 400 metres. Data showed that the quasistatic lateral wheel–rail forces are reduced when applying a friction modifier. The reduction is proportional to the reduction of the friction coefficient. However, the results revealed limitations in the interaction of the application strategy, the type of conditioning agent, the application system, and the operational conditions. When assessing the vehicle behaviour over two independent test tracks the quasistatic lateral wheel–rail forces were not uniformly reduced as targeted.

It could be shown that the standardised measuring method defined in EN 14363 is suitable to assess the dynamic vehicle behaviour in narrow curves when applying a top of rail friction modifier.

In comparison to stationary measurement methods for both friction and lateral forces, the continuous measurement of wheel–rail forces using measuring wheelsets allows an evaluation of the vehicle behaviour over all curves of a complete line. As the results may vary significantly along a track this method provides more profound information than a stationary measurement method.

Implementation and open questions

Friction coefficients measured in the laboratory are found to give a clear indication on how a certain friction modifier influences the vehicle behaviour. Even though the exact friction values determined in the laboratory or on track might differ, their relative behaviour is the same. Additionally, it can be stated that the two tested and already established standardised measuring methods are suitable to assess the performance of a friction modifier in track as well as in the laboratory.

Furthermore, the on-track tests showed the necessity to ensure that the application strategy, the type of conditioning agent and the application system are suitable for the given operational conditions in order to take full advantage of the benefits.

Deliverable(s): D3.4

48 Prediction of crack growth in the rail head

Mohammad Salahi Nezhad, Fredrik Larsson, Elena Kabo, Anders Ekberg, *Chalmers University of Technology / Trafikverket*

Background

Railways are an inevitable part of modern societies and generally provide safe and reliable operations. Due to increased demands in the last decades and limited flexibility of the railways, efficient maintenance has become more crucial. Fatigue crack growth, and especially rolling contact fatigue (RCF) crack growth, is the major deterioration factor and one of the foremost cost drivers in railway operations and maintenance. It can also cause train delays, traffic disruptions, and in the worst-case derailments.

In recent decades, extensive research and development efforts have been put into combating and predicting RCF. The overall risk of RCF initiation can to a large extent be predicted. However, predictions of time to initiation and crack growth, in terms of direction and rate of propagation, are afflicted with large uncertainties, especially when it comes to the question of how different operational factors affect the evolution of the RCF cracks.

This work focuses on investigating and developing methods to predict crack progression in railway rails. More specifically, a numerical framework for predicting the growth of individual cracks during operational load cases corresponding to passing traffic has been developed. This predictive framework can be used to evaluate the influence of different parameters on the crack growth. Ultimately, a calibrated framework can be used as an aid in predicting crack growth in field.

Increased knowledge and implementable results

In a two-dimensional (2D) modelling framework, a rectangular model represents a coupon of a rail in the longitudinal direction of a track. The rail features an inclined surface-breaking crack, which can have friction at its surfaces. The considered operational load cases in the framework are wheel–rail contact load, rail bending (as a result of a passing wheel) and thermal loads induced in rails as a result of winter conditions, both individually and in combinations.

The results show that the crack deviates transversely into the rail under high thermal/bending loads, which poses obvious threats due to the increasing risk of rail break. On the other hand, the crack grows shallowly into the rail under pure contact load and for low thermal/bending loads. Although this case is less dangerous, it still can cause costly maintenance.

For further analysis, a three-dimensional (3D) version of the numerical framework for the same problem has been developed. This can provide more realistic predictions compared to the 2D model but needs higher computational effort. Figure 48-1 shows the 3D rail model and an example of the evaluated crack paths and rates under pure contact load from the 2D framework for different levels of crack face friction.

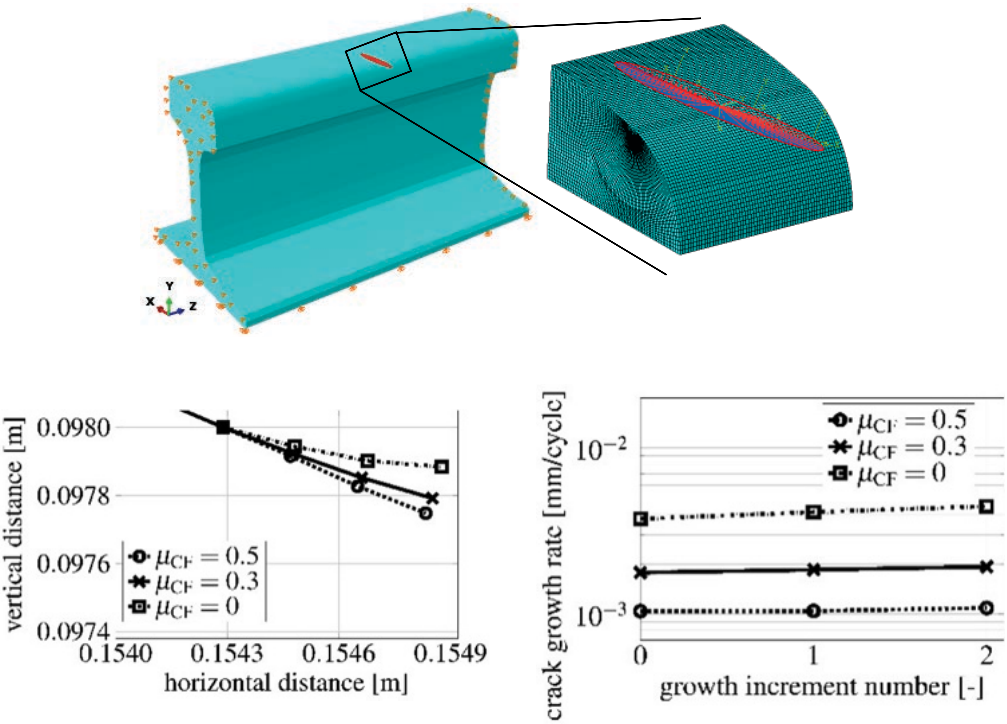


Figure 48-1 (top) A 3D rail model with a gauge corner crack. (bottom left) Zoom-in of predicted 2D crack paths for different levels of crack face friction (μ_{CF}) under pure contact load. (bottom right) Predicted 2D crack growth rates for different levels of crack face friction (μ_{CF}) under pure contact load

Implementation and open questions

The 3D framework will be further developed to account for more realistic predictions. Thereby, the qualitative 2D predictions can be replaced by quantitative predictions using proper model calibrations. In addition, some phenomena such as a lateral distance between the contact load and crack position can only be captured using 3D models. At the same time, this increases the number of parameters that can be considered in the framework, and significantly increase the computational effort. In addition, the calibration of the more realistic model can also be difficult due to the (large) scatter in the field measurements and observations. A challenging task here, which is still an open question, would be determining the most influential parameters to capture the desired phenomena while keeping the computational effort reasonably low.

Deliverable(s): D3.3

49 Anisotropy in rails

Magnus Ekh, Johan Ahlström, Daniel Gren, Nasrin Talebi, *Chalmers University of Technology / Trafikverket*

Background

Rolling Contact Fatigue (RCF) crack initiation is often associated with the accumulation of plastic deformation in the surface layer of rails and wheels. The behaviour and strength of this highly deformed and anisotropic layer are thus key properties of a rail or wheel material. A difficulty with analysing the material properties in the surface layer of a used rail, is the spatial gradient in strain and microstructure that develops with service life. An experimental technique to analyse and measure such properties in deformed material with a well-defined, homogeneous strain level was developed and exploited at Chalmers within In2Track2. The axial–torsion testing machine used for this technique makes it possible to prepare anisotropic material with a microstructure comparable to that found close below the rail surface and then to subject this homogeneously strained material to RCF like loading conditions.

The objective of the work in this chapter is to analyse the pearlitic R260 rail material both experimentally and numerically under such loading conditions. The analyses are conducted of both initially isotropic material and anisotropic material to improve the understanding of its characteristics and performance over time. In addition, the experimental analyses give data to improve mathematical models and numerical simulation tools that can be used to predict material behaviour. Both the improved understanding and the simulation tools can support the rail manufacturers and infrastructure managers to improve manufacturing, inspection and maintenance actions.

Increased knowledge and implementable results

An experimental study of fatigue crack growth has been conducted, where pearlitic R260 rail test bars were pre-deformed to varying levels using the method developed in In2Track2. The pre-deformed test bars were then machined, and notches were introduced to steer crack initiation. The test bars were then subjected to cyclic axial loading. The crack propagation rate and the crack path on the surface were measured for each test bar at regular intervals. It was found that the crack propagation resistance was significantly increased for pre-deformed test bars when compared to undeformed test bars while the difference in crack propagation resistance for the different pre-deformation magnitudes is small, see figure 49-1. The direction of crack propagation became similar for the different test bars.

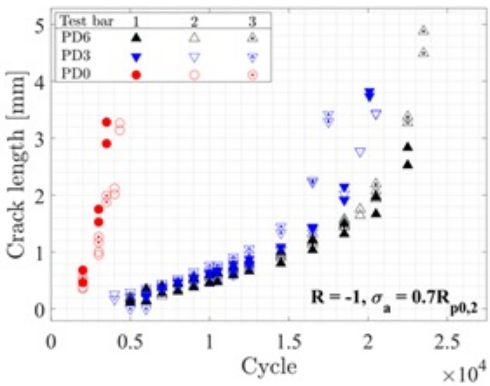


Figure 49-1 Fatigue crack length on for all test bars (three bars for each pre-deformation level) subjected to a nominal stress amplitude of 70% of the offset yield strength Rp0.2. PD0 refers to no pre-deformation while PD3 and PD6 refer to pre-deformation to 0.66 and 1.37 surface shear strain, respectively.

A plasticity model with anisotropy evolution has been proposed. The anisotropy evolution and the cyclic multiaxial behaviour from experiments of R260 steel can be captured well. This gives the possibility to compute accurate stresses and strains in the surface layer of rails during service life, which is essential for reliable predictions of crack initiation and growth in the surface layer.

The number of cycles to failure of highly deformed solid cylindrical test bars has been used to investigate the predictive capabilities of two commonly adopted RCF criteria (Jiang–Sehitoglu and Kapoor). The finite element method was used together with the developed plasticity model to predict the inhomogeneous stress–strain conditions in the solid test bars. The RCF criteria have then been applied to the stress and strain histories. From the results, it was concluded that the Kapoor criterion was not able to predict the number of cycles to failure for the experiments in a satisfactory way. However, the Jiang-Sehitoglu criterion gives a good agreement between the numerical and experimental data.

Implementation and open questions

The applied experimental procedure and proposed models for the rail surface layer need further validation against field results. Additionally, refinement and enhancement of stress-strain behaviour and fatigue crack initiation models are crucial for more realistic predictions. The utilization of multiaxial cyclic experiments with a higher number of loading cycles is recommended to improve and validate these models. Accounting for the complete fatigue life, including the macroscopic crack propagation regime developed in D3.3 Chapter 5.2.1, is essential. Future studies should integrate these developments with experimental results and model advancements. However, the challenge lies in achieving such simulations with reasonable computational efforts.

Deliverable(s): D3.3

50 Mitigation of ground-borne vibrations

Aires Colaço, Alexandre Castanheira-Pinto, Paulo Soares, Pedro Alves Costa, *University of Porto*

Background

Prediction and control of ground-borne noise and vibrations are one of the largest environmental challenges for railway exploration in urban areas. Nowadays, there is a shift at national and global level, in which investment in rail transport takes precedence over other transportation options, in a final attempt to drastically reduce CO_2 emission. The expansion and improvement of the railway network, associated with the high standards of comfort required by modern societies, requires the assessment and mitigation of the environmental impact induced by the implementation of such infrastructures in nearby buildings, more specifically in their inhabitants and in the operation of sensitive equipment.

In the context of predicting ground vibrations, various existing alternatives provide the desired level of accuracy, despite of structural complexity of the system. These alternatives range from empirical to advanced numerical tools. Based on these methodologies, it is possible to analyse the entire system, from the vibration source (vehicle–track interaction) to the receiver (building), taking into account the main patterns associated with the physical problem. Numerical tools are able to be used in the design and efficiency evaluation of mitigation countermeasures. In problems of this nature, the mitigation measures can be grouped according to the location where they are introduced. Thus, ground-borne vibrations can be controlled at three different levels: at the source, on the transmission path or at the receiver. This study specifically focuses on addressing the latter two categories, with the aim of designing an innovative mitigation measure and enhancing design capabilities for future initiatives.

Increased knowledge and implementable results

Taking into account the experience in dealing with these topics, the objective involves exploring two distinct mitigation measures: i) in the transmission path – through an innovative solution based on seismic metamaterial concept; ii) at the receiver – by employing a base-isolated building.

1 - Mitigation measures in the transmission path: innovative solution based on seismic metamaterial concept

The mitigation solution consists of an array of pillars with a vertical orientation (the most practical solution) as can be seen in the figure to the right.

Initial studies were conducted using a 2.5D FEM-PML (Finite Element Method-Perfectly Matched Layer) numerical approach, enabling the identification of the main phenomena contributing to the attenuation provided by the measure, with particular emphasis on the effect of group interaction. This phenomenon, known as "sonic-crystal" effect, induces a band-gap in the vibration response, which interval can be determined in based on the properties of both the ground and the pillars.

Based on the theoretical concepts related with the "sonic-crystal" effect, some experimental activities were developed next to a renewed stretch of the Portuguese railway network ("Linha do Norte", that connects Lisbon to Oporto), near Carregado, in Portugal. The experimental campaign allowed to evaluate the performance of the mitigation measure, with the main outcomes aligning closely with the anticipated results, i.e., an overall attenuation of the ground response after the barrier and the existence of a band-gap in the frequency range expected from the design procedure.

2 - Mitigation measure at the receiver: base-isolated building

The performance of an elastomeric bearing system as a mitigation measure was also analysed. The selected case study corresponds to a library that was constructed in the vicinity of a shallow underground metro line in the surroundings of Barcelona. Due to the building's proximity to the tunnel and its sensitivity, a vibration mitigation measure was recommended during the design phase. Figure 50-1 presents a general overview of the case study.

Figure 50-1 General overview of the vibration isolation case study: left: physical building; right: numerical model.

Several experimental campaigns were carried out before and during the construction of the building, allowing the characterisation of the ground–building system. The obtained data was used in the calibration of a numerical model, guaranteeing that this model correctly reflects the real behaviour of the building. From the numerical study conducted, it was possible to assess the efficiency of the vibration base-isolated system, confirming an effective reduction on the vibration levels. Typically, insertion loss values exceeding 6 dB are observed for frequencies above 15 Hz. However, it is important to note that this value is specific to the current case study, and similar analysis should be conducted to ensure an appropriate design for other scenarios. More details can be found in deliverable D3.4.

Implementation and open questions

The efficiency and suitability of different mitigation measures are inherently linked to the specific conditions of the track–ground–building interface. Consequently, the design of these measures should be executed using appropriate numerical methodologies that allow for the exploration of diverse solutions. Through such an approach and in consideration of conducted studies, it can be inferred that the existing numerical tools are able to address the predominant challenges associated with mitigation of ground-borne vibrations.

Specifically, for the innovative solution involving an array of vertical pillars, it is recommended to scale up the experimental prototype. This scaling should involve the incorporation of pillars with larger diameters to assess the "sonic crystal" effect at lower frequencies, aligning with the specific requirements of the given situation.

Deliverable(s): D3.4

51 Mitigation of noise and vibrations

Jamie Wilkes, *Network Rail*

Background

Throughout In2Track2, Network Rail monitored 2 trial sites pre- and post-grinding operations to gather data on rail roughness after grinding and better understand the effect of rail roughness on pass-by noise. It was evidenced in this study that acoustic rail roughness immediately after grinding was high and took time and rail traffic to reduce. This raised the subsequent question of whether low rail roughness (TSI NOI compliant) track immediately after grinding or milling was possible.

The objective of this further research was to better understand the effect of both grinding and milling maintenance practices on rail roughness and roughness growth rates, and to understand the effect this has on pass-by noise. This research also aims to propose improved maintenance grinding/milling procedures to achieve low roughness and low noise immediately after intervention.

The World Health Organisation (WHO) have widely documented the impact of transport noise on human health; demonstrating the link to increased sleep disturbance, ischaemic heart disease and cognitive impairment in children. It is hoped that this research (and further research in the area) can help reduce the detrimental impact of railway noise on health and reduce the societal impact the railway has on the community it serves.

Increased knowledge and implementable results

The research has shown that whilst TSI NOI compliant track can be achieved immediately after maintenance (figure 51-1), it can only currently be achieved at targeted locations where roughness is already relatively low. Therefore, whilst it is possible to propose that maintenance limits for rail roughness could use the NOI TSI, this is not realistically practicable under the current operational environments for grinding trains due to the requirement to understand the wavelengths of concern before intervention.

It is also worth noting that at sites where defect removal is the priority and maintenance practices are focused on factors other than noise, this targeted maintenance may not be practical. For this reason, the application of this research should be used in targeted applications (where noise may be a primary concern, such as in densely populated urban areas) and the rail roughness should be known before treatment is undertaken. This research could be implemented by infrastructure managers with reasonable acoustic rail roughness measurement already in place. Here evaluation of the roughness could be done prior to machining to give confidence in achieving the low acoustic roughness presented in the results of this report.

Whilst the research demonstrates that TSI NOI compliant track may not be possible immediately after rail grinding, it is possible to target specific roughness wavelengths using targeted milling operational practices if properly analysed prior to metal removal.

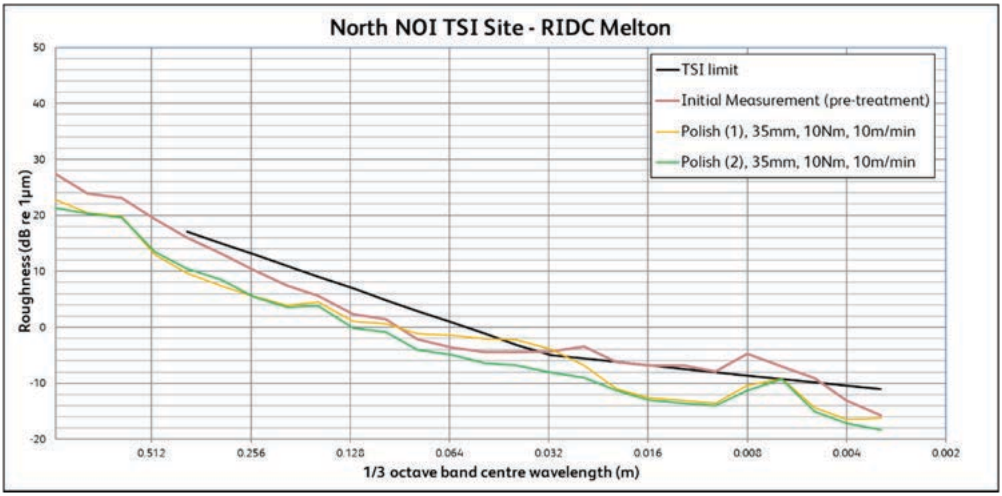


Figure 51-1 Reduction of rail roughness below TSI NOI limit

Implementation and open questions

The next steps for research in this area should examine the roughness wavelengths and machine operational parameters more closely and assess how these impact the noise directly. Additional locations (expanding the existing data) as well as testing of alternative machine types could further develop understanding.

The results hope to be implemented by applying similar research to existing operational maintenance vehicles. Using the learning and principles explored in this research, improved research on other existing grinding and milling machines can be explored to refine these techniques. Exploring how roughness grows after grinding and how it correlates to noise is also being researched.

The open question of maintenance limits for roughness of wheel and rail remains open, and a better understanding of the interaction between the two during railway operations (and the impact on noise) is still up for debate. In order to specify this more definitively, projects involving both train operators and infrastructure managers should be considered to create viable opportunities for improved future maintenance of both train and track.

Deliverable(s): D3.4

52 Predict and mitigate curve squeal

Astrid Pieringer, Jannik Theyssen, Wolfgang Kropp, *Chalmers University of Technology / Trafikverket,* Matti Rantatalo, Leevi Toratti, Florian Thiery, *Luleå University of Technology*

Background

Curve squeal is an intense tonal noise emitted by railway vehicles negotiating tight curves, which is experienced as highly annoying by both trackside residents and passengers. It is attributed to self-excited vibrations of the railway wheel during 'imperfect' curving. Modelling curve squeal poses a challenge since the phenomenon is non-linear and transient. Also curve squeal measurements are challenging since the phenomenon is more chaotic than deterministic. Squeal probability varies for nominally identical vehicles and also depends on the environmental conditions such as temperature and humidity that vary continuously. Curve squeal also depends on parameters that are difficult to control and to measure in field such as the local friction conditions in the wheel/rail contact and the contact positions on wheel and rail. As a consequence, it is also difficult to mitigate curve squeal. Mitigation methods such as the application of friction modifiers on the top of the rail or lubrication on the rail gauge corner work in some situations, but not in other.

This chapter, which is divided into two subtasks, addresses the mitigation of curve squeal at the source. Subtask 1 investigates methods to predict and mitigate curve squeal at the source with a focus on numerical simulations. The emphasis in subtask 2 is on field measurements and simulations. The main objective of this latter subtask is to investigate the possibilities of introducing acoustic maintenance limits for the wheel/rail interface with respect to track properties, especially the influence of track gauge and cant.

Increased knowledge and implementable results

In subtask 1, an in-house time-domain model WERAN for curve squeal has been extended from quasi-static to transient curving and connected to a SIMPACK model for low frequency vehicle dynamics. This approach allows considering realistic curving scenarios. Simulations with the tool showed that time-varying contact parameters such as contact position, lateral creepage, and friction coefficient can lead to on- and offset of squeal, see figure 52-1 for an example.

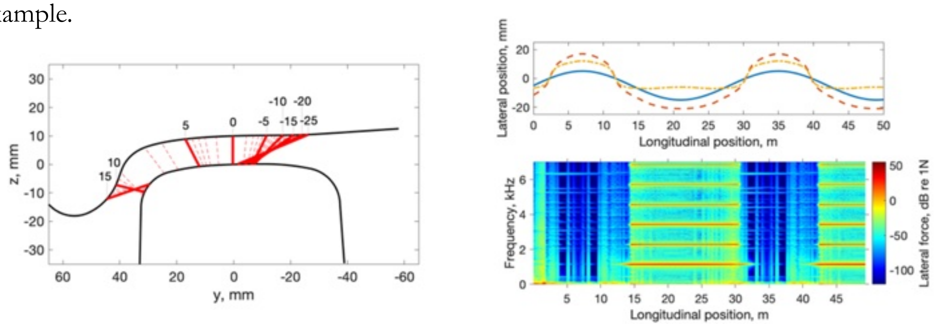


Figure 52-1 Squeal simulation for a prescribed sinusoidal lateral motion of the wheelset on the rail: Contact points for a nominal wheel profile S1002 on a nominal rail profile BV50 with inclination 1:40 calculated for different lateral displacements Δy_{WR} [mm] of the wheelset on the rail; results given for 1 mm steps (left). Prescribed relative motion of the wheelset on the rail Δy_{wr} and corresponding motion of the contact point on the wheel y_w and on the rail y_r (upper right). Corresponding spectrogram of the lateral contact force for a train speed of 30 km/h and a lateral creepage of -1% indicating squeal between a longitudinal position from about 14 to 33 m and from 42 m (lower right).

The history of the wheel/rail dynamics can also influence the occurrence of squeal and the squeal frequency.

WERAN has been validated in an operational context by comparing simulations with results from a statistical analysis of on-board noise monitoring data from Stockholm metro. This investigation also showed that squeal occurs for a certain range of contact positions on the wheel tread. Consequently, measures moving the contact outside this range (e.g. an optimised rail profile) have a potential to mitigate curve squeal.

In subtask 2, a multibody dynamics simulations (MBS) were made based on a 300-meter radius curve with a known squealing noise problem. Simulations were used to predict vehicle curving, as imperfect curving is known to increase the risk for curve squeal. Parametric studies showed that a lower track cant and an increased vehicle cant deficiency improve vehicle alignment in the curve (see figure 52-2). Track gauge, which varied from 1435 mm to 1450 mm in the real curve, did not result in a significant difference in vehicle alignment in simulations. It was noted that a longer bogie wheelbase length worsens alignment and thus for a train with different bogie types, bogies with a long wheelbase might be more prone to squeal.

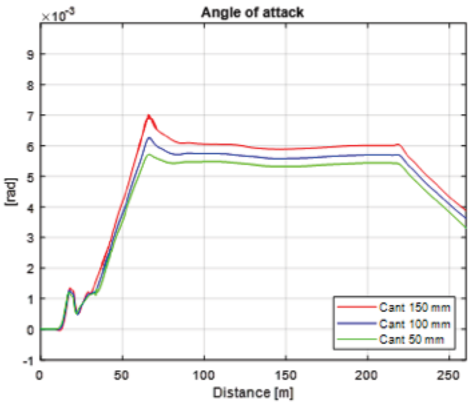


Figure 52-2 Predicted angle of attack of the leading wheelset for different track cants

Implementation and open questions

The extended version of WERAN connected to SIMPACK, developed in subtask 1, is an advanced tool for realistic curving scenarios, studying squeal occurrence and amplitudes. Further investigations with the model are necessary to clarify the influence of rail grinding and track parameters such as rail pad stiffness on propensity of squeal. Ongoing work aims to offer track design and maintenance recommendations for reduced squeal. In Rail4Earth, the developed tool is used to study the influence of wheel design on curve squeal.

As the simulations in subtask 2 suggested that a lower track cant and increased cant deficiency improved vehicle alignment in the curve, the next step is long-term monitoring of the curve to reveal any statistical correlations between train speed and curve squeal. In the future, the simulations are also planned to be done with measured rail profiles and a set of measured wheel profiles to see if vehicle curving is sensitive to different profiles.

Deliverable(s): D3.4

53 Reduced noise after rail machining

Urs Schönholzer, Emilie Freud, *SBB CFF FFS*

Background

Grinding of rails is an important part of rail maintenance. Rail damage caused by rolling contact fatigue needs to be removed to maintain safe and cost-effective operations of railway tracks. Corrugation needs to be removed from the rail surface to limit undesired noise emission from a corrugated track and to prevent premature track degradation. In addition, the transverse profile of the rail is reprofiled for achieving a favourable contact geometry between wheel and rail. One of the drawbacks of rail grinding is a temporary increase of perceived noise emission and corresponding complaints from lineside residents. Dry grinding with rotating cup-wheels leaves grinding marks on the surface of the rail perpendicular to the longitudinal direction of the rail. These grinding marks can generate noise when a train passes over that track. The surface marks are removed over time by regular traffic. However, the sometimes unpleasant tonal noise can be witnessed by lineside residents for weeks or even months after grinding depending on the traffic frequency. In our work, we assess the surface quality after different rail grinding procedures and quantify their impact on pass-by noise.

Increased knowledge and implementable results

A demonstrator grinding site has been chosen to compare a standard grinding and an optimised acoustic grinding process. A total of two nightshifts have been done by a regular track grinding machine, with each shift having one standard grinding section and one acoustic grinding section. The acoustic grinding was labelled as such by the grinding services provider. They did not disclose the exact changes that have been done to the machine for confidentiality reasons. The rail surfaces have been assessed on a total of four sections of track on a double track line (East and West track), two with standard grinding and two with acoustic griding, respectively. The noise on all four sections has been measured. The experimental setup has been chosen in a way that there was one microphone for the two tracks, at both the North and South sites. The measured pass-by levels have been adjusted accordingly for the variation in distance to the microphone. The NorthWest and SouthEast sections had acoustic grinding, NorthEast and SouthWest were with standard grinding. Results are described in figure 53-1. The single value denominator for acoustic roughness increases from 5 dB before grinding to 9 dB after grinding on the acoustic grinding site and from 4 to 12 dB in the conventional process. However, the pass-by noise measurements do not reflect this difference. In both sections, the noise immediately decreases after grinding, even though the roughness values increase before they start to decay. The rather quick decrease in roughness does not similarly translate into decreased pass-by noise measured according to ISO 3095.

To confirm the results, the demonstrator test has been repeated at an additional site. A section with acoustic grinding and one with conventional grinding have been completed with the same grinding machine. The results of this repeated test have been similar to the first demonstrator test described above and are therefore omitted here.

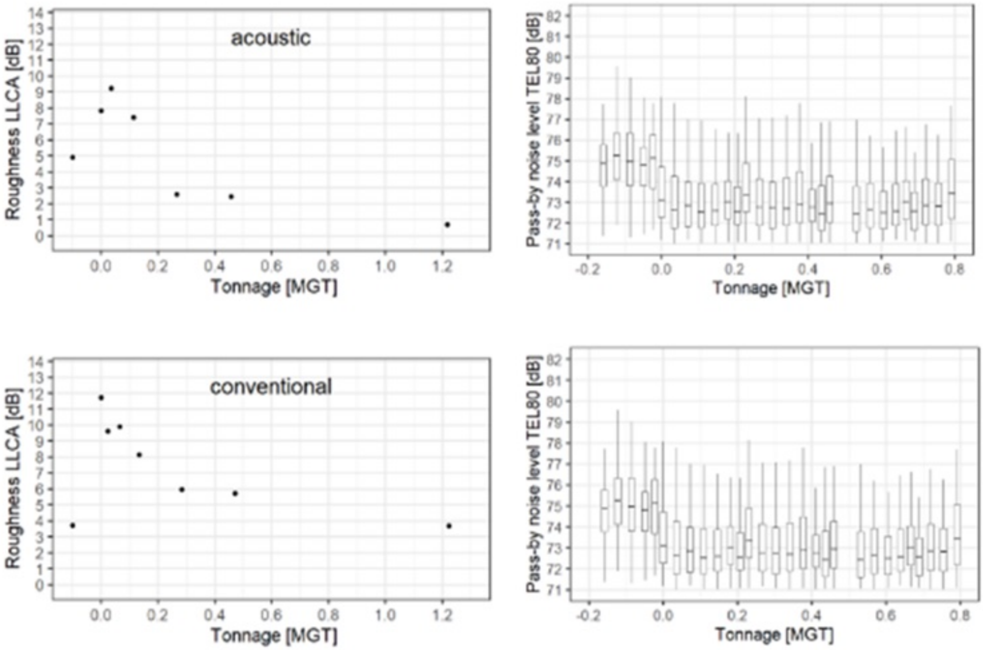


Figure 53-1 Measurements of the rail roughness single value denominator LλCA (top left and bottom left diagrams) and pass-by noise levels (top right and bottom right diagrams) of the two track sections on the southern site. The section with acoustic grinding is shown in the top row, the standard grinding process is shown in the diagrams in the bottom row. Please refer to the text for explanations.

Implementation and open questions

We have a very good maturity for the assessment of the mechanical rail surface and of the data acquisition in the field. However, it has become clear that the currently available normative single-value parameters are not well suited to describe the effects we intended to assess. This has been discussed with other railway infrastructure managers. There has been comparable work performed in parallel to the present project in the French and German networks. This was taken up by UIC's noise and vibration sector organisation, as most of the experts involved in the subject are already part of that group. Instead of suggesting another possible indicator for rail surface quality as result of the present project, the results will be contributed into the newly forming international project within the railway sector to join forces with the goal of developing a common assessment method for the rail surface quality after grinding. The group of interested parties will assemble in 2023 and begin work in 2024. The goal is to create a normative document for assessing the rail surface quality with respect to parameters relevant for noise emission after grinding that can be directly implemented for measurements in the field.

Deliverable(s): D3.3

54 Reduced noise and vibrations from slab track

Jannik Theyssen, Astrid Pieringer, Wolfgang Kropp, *Chalmers University of Technology / Trafikverket*

Background

The noise generated by trains on slab tracks tends to be louder than that on ballasted tracks. The primary reason behind this lies in the lower stiffness of the rail pad in slab tracks, which is necessary due to the higher mechanical impedance of the concrete support structure compared to the sleepers in ballasted tracks. The lower pad stiffness results in a slower decay of vibrational energy along the rail, and consequently in higher noise levels. While increasing the rail pad stiffness would lead to reduced noise, it would increase the loads on the track structure, ground-borne vibrations and rolling contact forces. This study aimed to address this conflict of interest. The goals of this study were threefold:

Firstly, we aimed to explore a potential solution to reduce both noise and vibration in slab track operations. Specifically, we investigated existing elasticities on slab tracks with booted sleepers for each rail seat. The idea was to increase the rail pad stiffness while providing a softer support beneath the sleeper, potentially decreasing rolling noise without sacrificing acceptable vibration isolation.

Secondly, we conducted a measurement campaign at an In2Track3 demonstrator at the iron ore line at Gransjö in Northern Sweden. The objective was to compare the noise radiated from a slab track section to that from a ballasted track section. The slab track section featured a two-stage elastic support similar to our first objective, providing a way to validate our model and enabling a comparison between slab track and ballasted track noise levels.

Thirdly, due to delays in planned tests, additional work was carried out, focusing on modelling noise radiation from railway wheels. This step was relevant for quantifying potential increases in sound radiation predicted in the first objective and validating the complete model from the second objective.

Increased knowledge and implementable results

The idea of the first objective showed promising results in our numerical simulations. By reducing the elasticity below the sleeper while increasing rail pad stiffness, the radiated noise can be significantly decreased while forces on the track structure are not increased.

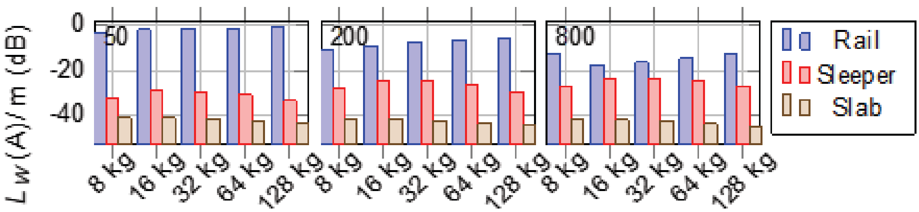


Figure 54-1 Sound power radiated by rail, sleeper and slab for various rail pad stiffnesses (50, 200 and 800 kN/mm) and sleeper masses (8 kg to 128 kg). The sound power is relative to the maximum observed sound power in the study.

The figure above shows the sound power radiated by the rail, the sleepers and the slab surface for different combinations of rail pad stiffness (50, 200, and 800 kN/mm) and sleeper mass (8 kg to 128 kg). The stiffness below the sleeper is 40 kN/mm in all cases. We can see that the rail is the dominant noise source in all cases, followed by the sleepers and then the slab. The radiation from the slab is insignificant compared to the other two, and even the sleeper contribution is insignificant at 50 kN/mm and 200 kN/mm rail pad stiffness. The radiation from the sleepers increases with increasing rail pad stiffness, while the radiation from the rail decreases significantly.

The effect of the mass and the elasticity below the mass is not as visible in the image. The study showed that that these parameters have a large effect on the rolling contact forces and track loads.

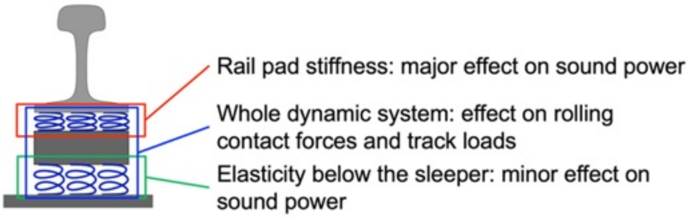


Figure 54-2 Conceptual overview over the results. Tuning the components appropriately can lead to reduced noise while not increasing track loads.

The Swiss railway operator SBB tested this method in the field, demonstrating its implementability. However, their measurements showed no substantial improvement in terms of the radiated noise. This discrepancy should be further investigated.

By comparing the developed model to the measurements carried out in Gransjö, we learned that the proposed numerical model is suited to predict the dynamic response of the investigated tracks, the rolling contact forces and the vibrations in the track structure during pass-by. The model can therefore be used in the design of ballasted and slab tracks.

Investigating the radiation characteristic of the researched wheel showed that only a few modes contribute significantly to the pass-by sound pressure. This knowledge and the proposed model can be used to optimise noise mitigation measures for railway wheels such as wheel dampers.

Implementation and open questions

A next step is to integrate the developed modelling tools for the acoustic radiation from railway track and wheels into existing in-house simulation tools, such as WERAN and DIFF, which are both time-domain models. These time-domain models for sound radiation from railway track can provide an insightful tool for researching, among others, human responses to railway noise and especially the temporal patterns in the signals.

In terms of the modelling, several questions are still open: It is unclear how much the sound radiation model of the wheel could be simplified before differences are audible or relevant spectra are affected. The same is true for the radiation model of the track. Aiming for an engineering model, these questions could be relevant to investigate.

Deliverable(s): D3.4

BRIDGES AND TUNNELS

55 Tunnel structural monitoring using fibre optics

Pierre Poggi, *SNCF Réseau*

Background

Tunnels differ from other structures because of the difficulty to accurately assess the supported loads, especially for old tunnels. The quality of structural monitoring is essential to improve safety in existing railway tunnels, especially:

- In severely degraded structures with serious damage (lining cracks and structural deformations)
- When repair works are delayed or pushed back
- During major repair works, which affect load supporting structure
- If third-party works are performed near existing structures
- In the context of tunnel affected by tunnel ground movement (slope instability, development of cavities, swelling and squeezing ground)
- For long-term structural health monitoring

The Optic Project aims to study and test new tunnel monitoring technique based on fibre optics. The fibre optic sensing (FOS) technology developed for other industry is adopted and tested in the lab as well as on site, in a tunnel. The type of optical fibre tested (Brillouin) has the advantage of enabling deformations to be measured along the entire length of the fibre, unlike traditional deformation measurement methods such as topography.

It was aimed to provide bases for improving the structural health monitoring of existing tunnels using fibre optic sensors. The improved structural health monitoring helps decision makers to better plan and optimise the maintenance operations and also to reduce the risk and impact on the traffic.

Increased knowledge and implementable results

The experimentation was carried out over 3 years, including 2 years of on-site measurements in the Encombrouze tunnel.

One of the main constraints is the resistance of the fibres to events occurring in this type of tunnel, in particular reinforcement work using shotcrete. The tests carried out in Marseille in June 2020 allowed the identification of 4 references of Brillouin optical fibres which are resistant to dry process shotcrete.

Figure 55-1 Resistance test support – before / after

As the fibre optic sensor is still sensitive to knocks and handling, any section of fibre installed must be mechanically protected, it must not remain exposed to air. The sections of measurement length not sealed or waiting for concrete spraying must be temporarily protected by means of protective devices.

The sections outside the measurement area can be laid out in cable trays, up to the connectors, to be placed in locked cabinets. The risk is that spot damage to the fibre can mask the length behind the damage. In order to reduce the stakes, in case of multiple fibres, a parallel mesh should be preferred to a serial mesh, as the latter potentially results in a much higher loss of measurement length in case of point damage on the fibre.

The measurements with FOS sealed in the structure (in shotcrete for example) allow a distributed, precise, and faithful measurement of the longitudinal deformation of the sealing medium. The need for accuracy is of the millimetre order. Therefore, measurements with sealing are suitable for deformation monitoring in old tunnels.

In contrast to measurements with sealed FOS, those without sealing (where the fibre is not sealed in the structure over its measurement length but simply fixed on it) are not recommended. The stiffness of the fibres prevents a continuous fixation, so the fixation is done per point.

Consequently, the measurement step depends mainly on the fixing step, which clearly attenuates the precision for measurements of millimetre order and is consequently not compatible with the type of monitoring which we seek to carry out in old tunnels. Moreover, the fixing points can deteriorate with time, especially in the case of gluing, for example due to humidity and freeze/thaw cycles.

Figure 55-2 Fixation with facing irregularity

Implementation and open questions

The observations made during the experimentation lead to the conclusion that monitoring via Brillouin optical fibre can be relevant for monitoring deformation of some old tunnels, under certain conditions. Considering the conclusions of this experiment concerning the sealing of the FOS in the structure, the most common use case will be the association of this FOS with shotcrete reinforcement works. The preferred use cases will therefore concern tunnels with evolving deformations for which reinforcement work is planned. There, the fibre can be used to analyse the impact of the reinforcement on the deformations, as well as the behaviour of the reinforcement.

The Brillouin fibre can also be used during the temporary phases of an operation, for monitoring temporary reinforcement elements such as struts or stiffeners. As the Brillouin fibre needs to be sealed, it can also be considered to be placed via a groove in the existing facing, without necessarily associating it with a new shotcrete shell. However, the fibre would be sealed via mortar in the groove, and the ageing of this mortar may affect the precision sought for the measurement. This process has not been tested during this investigation.

Deliverable(s): D5.1

56 Adaptable and tailored tunnel lining

Joaquim Barros, *University of Minho*

Background

A high percentage of railway tunnels (RT) in Europe present several types of structural damages and deficient geometry and functionalities, making them inadequate for the circulation of the new generation of high-speed trains in safe and comfortable conditions. Since the option for building this type of infrastructure is quite expensive (about 25M€/km and 75M€/km in non- and adverse geotechnical conditions, respectively), their rehabilitation and upgrading are sustainable options, as long as efficient and cost-competitive solutions are available and reliable.

A multiscale and multilevel strategy was developed for the design of a sustainable and cost-competitive strengthening solution for RT by using Fibre Reinforced Concrete (FRC) applied according to a new shotcrete technology (Fibre Reinforced Shotcrete, FRS) supported by robots and sensors.

Since the 1990s, the use of FRS has gradually increased in tunnel stabilization and rehabilitation, due to the potential of fibres to replace steel meshes with technical and economic advantages. However, the available FRS technology does not allow the optimum use of FRS, and current design methodologies do not consider the soil-structure interaction in a multiscale framework. These are topics which are addressed in the conducted research.

Increased knowledge and implementable results

Figure 56-1 shows a RT suffering damage due to the dislocation of an unstable block of rock in the top part of the tunnel and the presence of a zone of week soil (region of θ_1 from 60° to 90°).

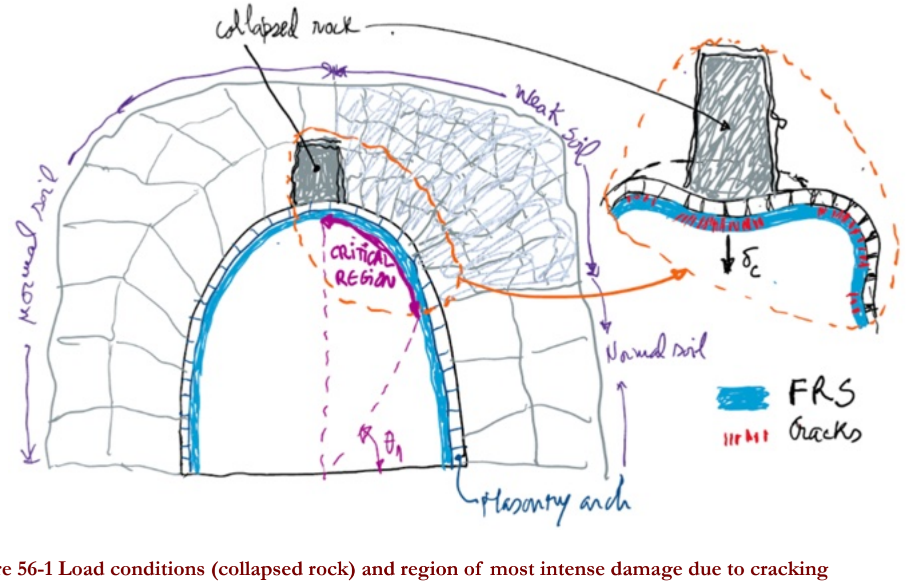


Figure 56-1 Load conditions (collapsed rock) and region of most intense damage due to cracking

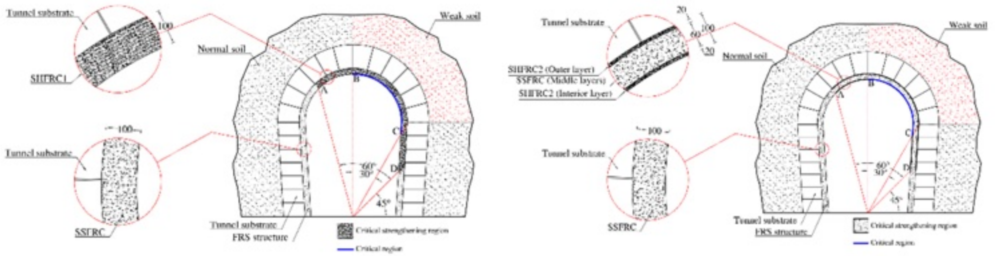


Figure 56-2 Strengthening plans using FRS of different mechanical properties: a) StrPlan1; b) StrPlan2

Two strengthening plans using the proposed technology are shown in figure 56-2, and their efficiency is terms of restoring the stiffness and load carrying capacity of the damaged RT is presented in figure 56-3.

Considering 1 km^2 of RT requiring strengthening intervention, an economy of 53M€ and a reduction of 22.5kT of CO_2 emissions is obtained when adopting the StrPlan2 over an existing strengthening technique that uses conventional materials.

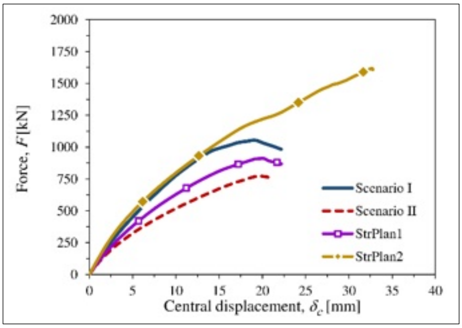


Figure 56-3 Load-deflection of undamaged (Scenario I) and damaged (Scenario II) RT, and after strengthened according to StrPlan1 and StrPlan2

Implementation and open questions

The aimed next steps are:

- Building Information Modelling should be used for obtaining RT's digital twin, incorporating 3D geometry, geotechnical and damages information from the most recent technology on inspection and diagnosis, and generating data files for design software
- Artificial Intelligence should be used for classifying the types of damage for prioritisation on the intervention decisions and to support structural analysis of the tunnel
- A new robot shotcrete system should be developed for applying the FRS according to the output of the structural design, being possible to have FRS of different properties by controlling in real-time the type and content of fibres

Deliverable(s): D5.3

57 Ground-based photogrammetry to create digital models of bridges

Jaime Gonzalez-Libreros, Gabriel Sas, Thomas Blanksvärd, Chao Wang, *Luleå University of Technology*

Background

In Europe, a significant part of the railway infrastructure, including assets like bridges, is ageing and often surpasses its originally intended lifespan. This emphasises the urgent need for maintenance and repair. To evaluate the condition of these bridges, various inspection methods, both destructive and non-destructive, are employed. These methods aim to identify problems such as deterioration of concrete, corrosion of steel reinforcement, water infiltration, delamination of concrete cover, spalling, settlements, and cracking, among others. While visual inspections are widely used due to low cost and speed, they have considerable drawbacks. They are time-intensive and the data lack detailed visualisation of defect locations or severity. The subjectivity of the inspectors' assessments affects the reliability and consistency of these inspections. Furthermore, visual inspections alone are insufficient and need to be complemented by other methods.

Hence, there's a pressing demand for new inspection and monitoring strategies for infrastructure that minimise traffic disruptions and enhance the efficiency and dependability of the data collected. Innovative techniques like Terrestrial Laser Scanning (TLS), Close-Range Photogrammetry (CRP), and Infrared Scanning (IS) are non-contact methods capable of rapidly gathering extensive data sets with high accuracy. Recent research indicates that Close-Range Photogrammetry (CRP) is particularly effective and cost-efficient for managing bridge inventories, although its use has been largely limited to specific, isolated instances. A detail assessment of this method was performed within In2Track3 to establish basic requirements concerning weather, equipment, and the expertise of personnel for the inspection of bridges using CRP.

Increased knowledge and implementable results

Close-Range Photogrammetry (CRP) surveys focusing on ground-based photogrammetry have been conducted to generate digital models of five bridges in Northern Sweden. The data from these surveys was then utilised to construct 3D models of the bridges and monitor damage progression over time.

The applied methodology is illustrated in figure 57-1 and encompasses three stages. In the first stage, data is gathered via photogrammetric surveys across the five bridges, varying in equipment used, weather conditions, and the experience level of the personnel. The second stage involves using this data to create 3D models of the bridges. The attributes of these models, such as accuracy, resolution, cost and efficiency of equipment, usability, portability, and time taken for data acquisition, were then compared. The third stage involves employing these models to identify damage. The findings are contrasted with results from previous surveys to evaluate how damage has evolved over time. The outcomes were analysed, and key considerations for conducting digital bridge inspection surveys were identified.

Results indicated that ground-based photogrammetry is suitable for extensive bridge surveying. It doesn't demand highly skilled personnel for gathering the necessary data to create

3D models. The results demonstrated that while higher-quality models were produced using more advanced equipment, more affordable options like GoPro cameras or smartphones are also viable for scenarios where less detail is sufficient. Consequently, infrastructure managers can delegate photogrammetric survey tasks to staff members who may not have prior experience in bridge visual inspection. The data collected in this manner can be subsequently analysed by bridge engineers in the office, enabling them to assess the condition of the bridges. Moreover, the level of detail provided by the 3D models far exceeds that of traditional visual inspections, facilitating more accurate evaluations of damage progression when these surveys are conducted regularly on the structures.

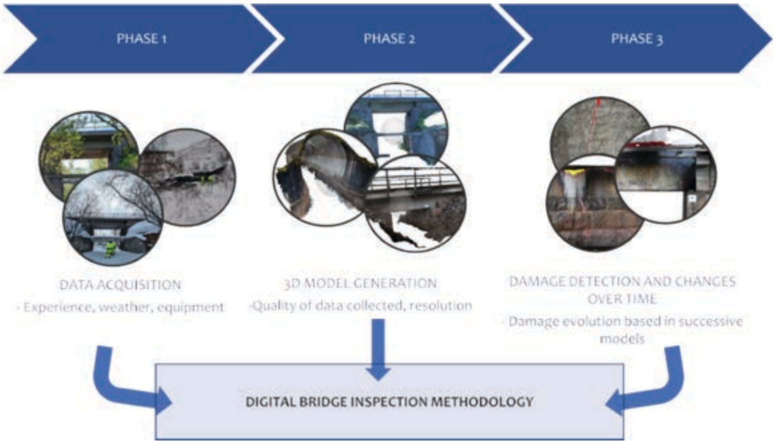


Figure 57-1 Schematic representation of the approach used.

Implementation and open questions

The research performed in the use of CRP for survey of bridges demonstrated that its application in routine inspections of existing railway infrastructure can be advantageous for infrastructure managers. As part of this work, a detailed step-by-step methodology to perform such surveys was developed. Future efforts should focus on the implementation of the methodology by training personnel on the use of the equipment and collection of the photos, and subsequent surveys of bridges located along national road and rail lines.

In this way, the industry will be able to move into standardised, fast, and more accurate inspection methods that can be easily followed by infrastructure owners and allow them to use CRP for the entire national road and railway lines instead of specific cases along those lines.

In addition, the combination of CRP surveys, generation and updating of 3D models of the assets, and automated damage detection can provide key information to stakeholders and infrastructure managers. When these techniques are put together, it is possible to have a more precise insight regarding the damage evolution of a given structure, that can be easily neglected by traditional visual inspections based only on in situ visits. Although extensive research is being performed nowadays for the development and training of algorithms for image-based damage detection, they are still not easily available for infrastructure managers, surveyors, and bridge engineers.

Deliverable(s): D5.4

58 Bridge underwater monitoring

Jose Solis-Hernandez, Paula Lopez-Arevalo, *Cemosa*

Background

In Europe, a considerable portion of railway infrastructure assets is approaching or has exceeded the intended design life. This situation highlights the pressing need for maintenance and restoration efforts. Implementing new enhanced inspection methodologies as well as proactive maintenance strategies is crucial to face this situation.

Inspections performed on partially submerged infrastructures are crucial since they imply a series of specific types of defects that can occur (corrosion, erosion, abrasion, biological growth, cracking, sedimentation etc) that can be missed since direct visual inspections cannot be performed. Traditionally, underwater inspections conducted by human divers are performed. These inspections involve a meticulous and labour-intensive process where divers equipped with specialised gear descend into the water to visually inspect infrastructure. This method, while effective, poses challenges due to the limited time and depth divers can spend underwater and the potential risks associated with working in confined spaces and challenging underwater environments. Besides the operation difficulties and safety issues, this kind of inspections are costly.

Inspection and maintenance also involve the generation and management of large volumes of data. This poses a new challenge of adapting to miscellaneous systems in a sector that currently exhibits a low level of digitisation. The diverse data must be efficiently stored, analysed, and presented to the infrastructure manager in a straightforward and user-friendly manner. The objective is to enhance services, decrease costs, and reduce emissions.

Increased knowledge and implementable results

Within the In2Track projects, a Remotely Operated Underwater Vehicle (ROUV) has been integrated for underwater inspection of infrastructures. Data gathered during ROUV inspections is enriched by integration of cameras, water quality sensors, a gripper, a unidirectional sonar and other navigation support sensors. figure 58-1 shows an example of the camera view of the ROUV during an inspection.

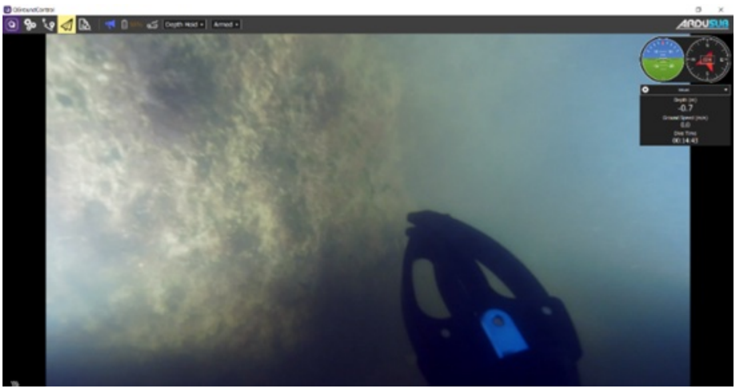


Figure 58-1 ROUV's camera view during inspection

ROUV can monitor the erosion of structural elements, scour of foundations and other types of common degradation. In comparison with traditional inspection the system is reducing inspection costs, it is reducing the exposure of workers to hazardous situations, improving manoeuvrability and flexibility, allowing access to hard-to-reach areas, providing real-time control of the inspection over longer periods and allowing extensive collection of inspection data thanks to the integration of the different components.

Data retrieved from inspections are integrated into a Digital Twin oriented Bridge Asset Management Platform. This platform integrates data such as dynamic information coming from IoT monitoring services, historic data from infrastructures, and inspection and maintenance information, such as the one coming from the ROUV. It features a user-friendly interface. The platform is based on a BIM-GIS environment which enables the interaction with static and dynamic data in different services to provide management, monitoring and analytics features, including predictive analysis of real-time data and condition state of infrastructures based on Operational Model Analysis and ML techniques. The monitoring interface of the platform is shown in figure 58-2.

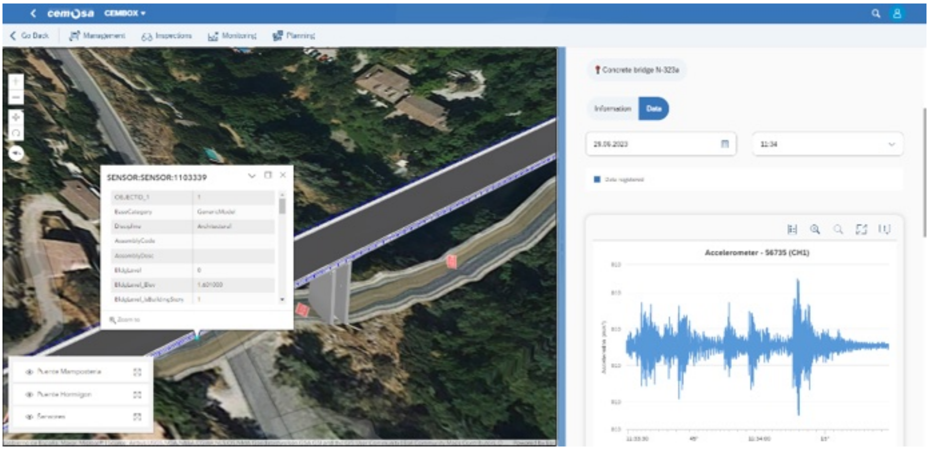


Figure 58-2. CEMBOX Infra Monitoring interface.

Implementation and open questions

The testing and demonstration on ROUV technologies and the integration of this information into a Digital Twin Platform has enabled the identification of potential future enhancements:

- New manipulators for the gripper to upgrade the ROUV
- The enhancement of the Graphical User Interface
- The installation of a 360° camera
- Development of computer vision algorithms to automatically process ROUV images

Furthermore, condition assessment technologies will be further analysed and enhanced. Operational Model Analysis techniques will be applied to monitoring data over large time periods to analyse the evolution of dynamic parameters. Machine Learning methodologies will be developed to assess health condition and make predictions on infrastructure status. Data driven approaches will be improved to detect anomalies.

Deliverable(s): D5.4.

59 Proposal for improved bridge design philosophy

Reza Allahvirdizadeh, Andreas Andersson, Raid Karoumi, *Royal Institute of Technology/Trafikverket*

Background

Increasing operating speeds of trains on modern networks presents new design challenges for infrastructure, particularly bridges, which were minor concerns in the past. This is primarily due to the resonance phenomenon that occurs when the frequency of imposed loads from passing trains coincides with bridge's natural frequency. Under these conditions, the bridge experiences excessive vibrations, far greater than those observed under off-resonant conditions. One safety concern arising from such conditions is the potential dislocation of ballast particles, often denoted as ballast instability.

These granular components transfer the imposed loads at the rail level to the bridge structure. Previous experimental studies have demonstrated that ballast instability can disrupt the load path, increasing the likelihood of train derailment. As a result, current design regulations restrict the vibration level of the bridge. From a philosophical standpoint, a safe system is not one that never fails. Rather, the probability of a system failing should be less than the level of risk that people are willing to accept in their daily lives. Therefore, designing a system inherently necessitates estimating its probability of failure.

Failure can be defined as a situation in which the imposed loads exceed the system's capacity to withstand those actions. However, these loads and resistances are not exactly known values, even though the system that the designers are tasked with designing is a specific object. Therefore, probabilistic methods are followed by design regulations to propose design approaches that ensure that the probability of failure remains below an acceptable level.

This objective can be achieved through various methods, such as maintaining a characteristic demand-to-capacity ratio below a specific threshold. This approach is often referred to as employing partial safety factors. It is evident that such ratios may vary from one specific design to another, but design regulations should recommend general values applicable to all possible scenarios. Therefore, various design situations should be considered, and an optimisation problem should be solved to determine the optimal values of partial safety factors that minimise the difference between corresponding failure probabilities and acceptable values. An alternative design philosophy can instead propose minimum requirements for the design, the fulfilment of which guarantees the achievement of the desired safety objectives.

To the authors' knowledge, neither of these approaches has been employed to propose current dynamic design regulations to prevent ballast instability. Therefore, this study enhances current design methodologies proposing frameworks based on both methods.

Increased knowledge and implementable results

A representative data-set for each contributing variable influencing the dynamic response of railway bridges (including those related to the bridge and passing train properties) were collected at first. Acquiring such data-sets provided the opportunity to assign appropriate theoretical probability distributions to each variable.

Subsequently, a diverse set of design scenarios, encompassing different bridge cross-section types, span lengths, and numbers of spans, were considered. For each scenario, the system's failure probability was calculated across various partial safety factors. Minimising the summation of these probabilities, subject to the desired safety level (or target reliability denoted here as β_t) across all considered design scenarios, can yield a newly calibrated partial safety factor. An example of this approach is presented in figure 59-1a. It should be mentioned that target reliability indirectly takes into account the acceptable risk level of the system. It is often defined by minimising the associated costs of construction, repair, maintenance and possible failures depending on different levels of probability of failure considered. Following this approach led to the proposal of a partial safety factor of γ_a= 1.38, traditionally being assumed as 2.0. Consequently, the new method allows the system to experience higher vibration levels, resulting in lighter bridges.

In the alternative approach, the minimum permissible bridge mass (denoted here as m) was considered as an optimisation parameter. The solved optimisation problem determines the minimum bridge mass for which the probability of experiencing excessive vibrations remains below the desired level. This approach led to the introduction of probabilistic design curves, as shown in figure 59-1b as a function of bridge span length (denoted here as L). Therefore, if the provided mass for a design exceeds the optimised values, the system would be considered safe with respect to ballast destabilisation.

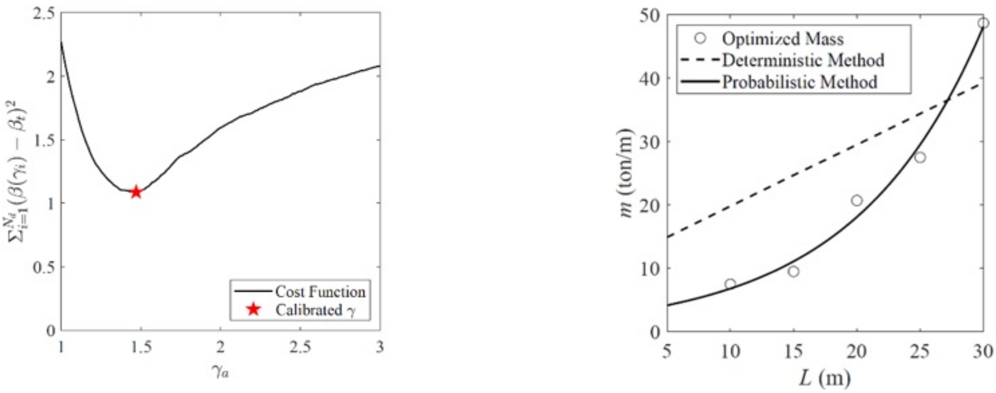


Figure 59-1 Improved design methods of railway bridges using probabilistic approaches. Left: Updated partial safety factor, Right: Minimum required linear mass of bridges

Implementation and open questions

Two distinct probabilistic frameworks are employed to enhance conventional design methodologies. These novel approaches meet the required safety standards and yield lighter solutions compared to traditional design techniques. Despite these advancements, numerous questions remain to be addressed in future research. More advanced computational models should be employed to simulate bridge behaviour, including 3D effects and train-system interactions. Additionally, the soil-structure interaction effects on system safety should be investigated. Moreover, environmental factors can significantly influence system behaviour; however, they are disregarded in the present study for the sake of simplicity. These effects require careful consideration in future research endeavours as well.

Deliverable(s): D5.6

60 Classification capacity

Tom Brodrick, *Network Rail*

Background

This study addresses the challenge of enhancing assessment methods for historical metallic half-through underbridges with offset U-frames, a prevalent configuration in the UK and Europe. The primary problem involves accurately determining lateral restraint (U-frame) on main girders, crucial for preventing buckling. The current assessment approach at different levels involves empirical methods, assumptions, and complex finite element analysis, with Level 2 requiring extensive time and resources.

There are over 300 such bridges in the UK and potentially thousands in Europe. The lateral restraint is influenced by cross-girder flexibility, joint rotational flexibility, and vertical stiffener/main girder web flexibility. The current methods can lead to conservative estimates, impacting infrastructure longevity and sustainability.

The project aims to develop analytical methods for Level 0 and 1 assessment (defined in figure 60-1), focusing on quantifying offset U-frame stiffness and effective length for accurate main girder buckling capacity evaluation. Cost-benefit analysis suggests significant savings by avoiding complex Level 2 analyses when Level 0 and 1 assessment suffice.

Stage 2 concentrates on the rotational flexibility of the cross-girder/main girder connection through laboratory testing and finite element modelling. The ongoing Stage 3 will extend sensitivity analysis to additional bridge and girder arrangements not otherwise covered.

The project's importance lies in providing cost-effective yet accurate assessments, potentially extending the lifespan of existing infrastructure and minimising the need for costly replacements or strengthening. The outcomes aim to influence industry practices, enhancing the efficiency and sustainability of managing historical metallic underbridges with offset U-frames.

Increased knowledge and implementable results

Significant progress has been made in addressing challenges related to assessing historical metallic half-through underbridges with offset U-frames. Three validated analytical methods now quantify restraint stiffness and determine main girder effective length with this restraint. These methods notably enhance main girder buckling capacity compared to the Level 1 approach assuming no restraints.

Multiple sensitivity analyses on alternative bridge arrangements and cross-girder to main girder joint stiffness confirm the applicability of the three analytical methods to a broader bridge population and across all of the Level 0, Level 1, and Level 2 assessment stages (figure 60-1). However, key risk areas remain regarding restraint component capacity: potential local yielding of the main girder web plate and brittle fracture risk in wrought iron main girder web plates, necessitating further work.

Validation of the rotational stiffness of the cross-girder to main girder joint was achieved through both laboratory testing and detailed finite element (FE) modelling. Additionally, the sensitivity of the proposed analytical methods to variations in these values was thoroughly assessed. Furthermore, the study explored a reduced form of restraint, where the cross-girder to main girder connection functions as a pin joint only. This investigation revealed a significant increase in the buckling capacity of the main girders compared to when no restraints are considered. Finally, typical stress hotspots were identified, predicting instances of localised yielding, and suggesting methods for accounting for these local effects.

		Main girder global buckling	Capacity of U-frame restraints
Level 0 Assessment	**A simplified assessment based on principal checks of critical sections and conservative load distribution.** **Network Rail has developed a suite of Level 0 assessment tools to support Level 0 assessment.** **First time assessment of structures using a Level 0 approach is generally based on record information and supplementary site investigations as determined by the Asset Engineer (AE)**	1. In2Track3 Method 3 (modified lucky dip) - gives L_e/L (see IR01) 2. Use BS5400-3 to calculate buckling capacity using existing formulae	1. Qualitative only (in-line with current assessment practice)
Level 1 Assessment	**A detailed assessment based on standard structural engineering design principles that takes greater account of load distribution, beneficial effects and other analytical assumptions.** **First time assessment of structures using a Level 1 approach is generally based on an Inspection for Assessment (I for A).**	1. In2Track3 Method 2 - gives δ_R (see IR01) 2. Use BS5400-3 to calculate buckling capacity using existing formulae 3. If buckling capacity insufficient, use Method 1 to refine calculation of δ_R and recalculate buckling capacity	1. Calculate F_R, F_S and F_L forces using existing BS5400-3 formulae but with modified δ_R and λ_{LT} as described in IR-02 (approach to be validated) 2. Use local FE model of panel to check local stresses from above restraint forces combined with global stresses in restraint components. Do note exceed yield strength (approach to be validated. 3. If elastic stresses exceed yield strength up to the required buckling capacity, a) If main girders are earlo or modern steel i. Allow localised yielding at ULS noting that buckling capacity should remain lower bound if Method 1 or 2 used, OR ii. Resort to Level 2 assessment if residual risk unacceptable b) If main girders are wrought iron, resort to Level 2 assessment due to risk of brittle fracture
Level 2 Assessment	**Use of more refined analysis, better structural idealisation and potentially material test information to refine a Level 0 or Level 1 Assessment.** **Most complex level, using some or all of: advanced analysis, statistical live load models, load tests or worst credible material strengths.**	1. Use NL FE analysis to assess capacity directly, including geometrical and material non-linearity and imperfections (see GN01). 2. Limit capacity based on acceptable displacement and	1. Capacity implicitly checked as part of global buckling capacity, but additional sensitivity required around initial imperfections to maximise stresses on restraints (see GN01)

Figure 60-1 Proposed assessment process for bridge with main girders restrained by offset U-frames across Level 0, Level 1 and Level 2 assessment stages

Implementation and open questions

The project identifies two key risk areas: the capacity of restraint components (specifically local yielding of the main girder web plate), and the risk of brittle fracture in wrought iron main girder web plates. To address these risks, further development and validation are recommended.

The next steps involve refining the proposed method for validating U-frame restraints at the Level 1 stage and ongoing work to assess the risk of brittle fracture in wrought iron main girders. This includes deriving suitable strain limits, model refinement, and developing a risk-based approach at the Level 1 assessment stage.

The research has raised new questions, leading to future work recommendations such as exploring the effects of skew, introducing a central main girder, removing plan bracing, replacing cross-girders with a continuous transverse deck, and extending the span range to 30m. All considerations will weigh the impact on global buckling capacity and local effects in offset U-frame restraint components.

Before incorporation into UK assessment standards, the proposed assessment approach and related work should undergo an independent check.

Deliverable(s): D5.5

61 Bridge damping and resonance

Artur Silva, Gonçalo Ferreira, Diogo Ribeiro, Pedro Montenegro, *University of Porto*

Background

Damping has a significant impact on the dynamic response of railway bridges, especially at resonance, which may strongly influence the design of new railway bridges or the evaluation of existing ones. An underestimation of it may lead to conservative results during the design phase, which can culminate in an increase of costs. Results obtained in the several experimental campaigns carried out by PORTO and KTH-TRV during In2Track2 demonstrated that the damping can be significantly higher than given by the European norm EN 1991-2. Moreover, the estimations showed a wide variety of values for the same structures, which may be related to the level of amplitude of the vibration to which the bridges were subjected. figure 61-1 illustrates part of these results, where it is possible to observe that most of the tests indicated damping levels significantly higher than the normative ones. This is particularly notorious in the Portal Frame type bridges, likely due to the radiation damping effect provided by the backfill soil. Therefore, it is of the utmost importance to continue the work from In2Track2 to propose a more advanced basis for design in terms of damping definition. Based on this, the main objective of the work in In2Track3 consisted of defining an advanced technique to estimate damping in bridges.

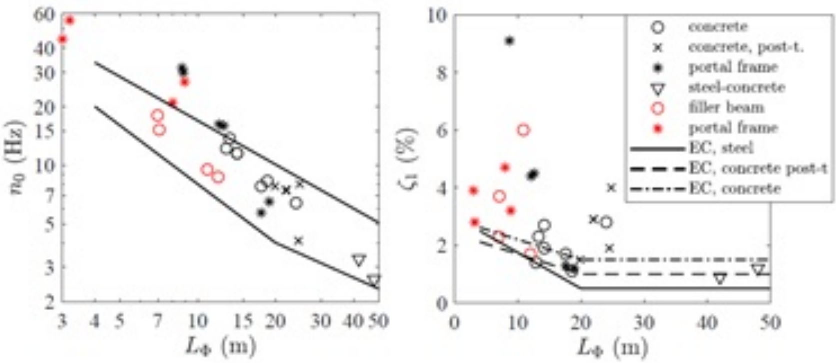


Figure 61-1 Experimentally found damping from the field tests carried out in In2Track2 on filler beam, portal frame and concrete beam bridges.

Increased knowledge and implementable results

A methodology to estimate damping coefficients on bridges based on the Prony method, as an alternative methodology to the classical Logarithmic decrement method was developed. This methodology allows to estimate damping coefficients in railway bridges with coupled and closely spaced fundamental modes of vibration using acceleration responses caused by train passages.

After validating this methodology with a numerical case study of a Portuguese bridge, it was possible to apply it to several experimental results obtained during the campaigns carried out in Portugal. Figure 61-2 (left) presents the results of damping coefficient values estimated with the proposed methodology as function of the maximum acceleration for the eigenfrequencies for four typical filler-beam bridges from the Portuguese railway network. It can be observed that for lower acceleration values there is more dispersion in the damping coefficient values, with variations between 1% and 11%. For higher acceleration values, however, the dispersion of the damping coefficient values tends to decrease, with variations between 4% and 6%. This means that adopting free vibration responses characterised by higher accelerations should be a good practice for damping estimation, since it considerably decreases the dispersion of values. Moreover, damping is particularly important at resonance where the accelerations reach high values, therefore, damping values estimated with low levels of acceleration should not condition the normative definition of damping. Figure 61-2 (right) shows the same results but as a function of bridge span length for comparisons to ERRI-D214 for filler-beam bridges and the lower limit for the damping coefficients adopted by EN 1991-2. It can be observed that, for span lengths between 4m and 8m, the results obtained with the proposed methodology agree well with the results from ERRI-D214 database. However, for span lengths between 10m and 12 m, the results of the Prony method are more dispersed, due to the low acceleration levels at which the damping coefficients were calculated.

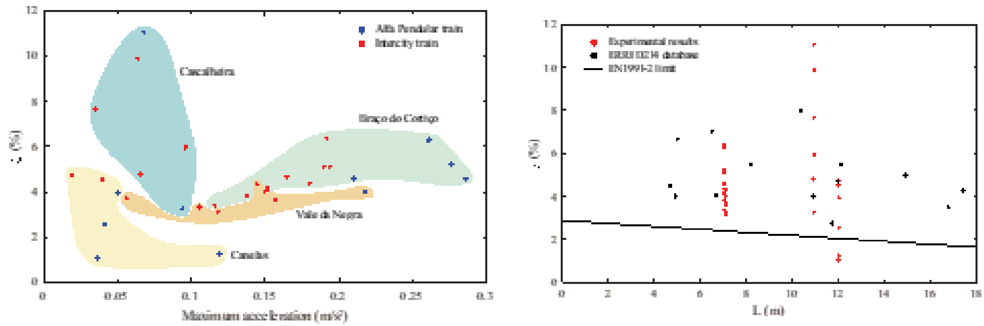


Figure 61-1 Damping coefficient estimates based on the Prony method for the four filler-beam bridges as function of the maximum acceleration (left) and the span length (right).

Implementation and open questions

The results obtained show that the proposed methodology should be applied for higher acceleration records to obtain more precise damping coefficients. These results may be seen as a first step to update to the ERRI D214 database and further revise the EN 1991-2 regarding limits for damping coefficient values. Moreover, it is expected that the proposed methodology should be applied soon to a much wider range of bridges to obtain more answers regarding the typical damping scatter observed in measurements. Such objectives are now being pursed in the recently awarded EU-Rail Project “InBridge4EU – Enhanced Interfaces and train categories FOR dynamic compatibility assessment of European railway BRIDGEs”, in which work package 4 is fully dedicated to the provision of new recommendations for the Eurocodes regarding bridge damping.

Deliverable(s): D5.1 & D5.6

DEMONSTRATORS

Photo: Rikard Granström

62 3MB slab track

Carlos Hermosilla, *Acciona*

Background

As infrastructure capacity requirements, axle loads and maximum speeds increase, the issue of resurfacing becomes more and more relevant. Higher axle loads increase track degradation, but higher speeds reduce the acceptable track settlement. At the same time, capacity demands lead to shrinking maintenance windows. It is for this reason that slab track systems were developed: by exchanging ballast for a slab as rail support, the recurring problem of tamping was removed.

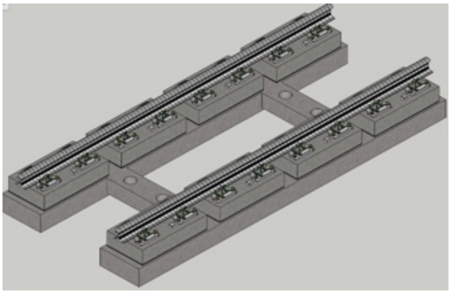


Figure 62-1 The 3MB system

Yet ballast-less tracks brought their own problems: higher initial costs, longer installation times, increased noise and vibration, disruptive repairs in case of slab failure, and the inability to readjust geometry at settlements. The Moulded Multi Modular Block (or 3MB) system was developed to bridge the gap and address the most common slab track issues while keeping its advantages.

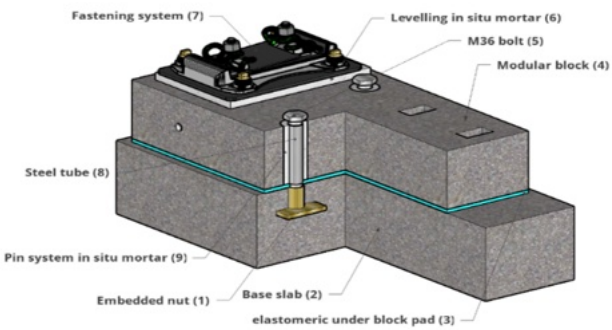


Figure 62-2 3MB fastener-block-pin assembly

The 3MB system is composed of a ladder-shaped precast concrete slab, on which eight precast concrete blocks are placed, four on each arm of the ladder. Each block holds two consecutive rail fasteners, connected to the blocks on site by means of levelling mortar. Under each block, an elastomeric mat provides noise reduction and vibration isolation. Horizontal block movement is restrained by pairs of 'pins', threaded steel bolts enveloped by lubricated cylindric steel jackets. The bolts are screwed onto nuts embedded in the slab, while the steel jackets are connected on site to the blocks with mortar. Thus, blocks may move vertically and benefit from the elastomer.

The main feature of the system is that any block may be removed laterally with no need to demolish concrete or lift the rail, enabling fast repair and geometry adjustments in case of settlement.

Increased knowledge and implementable results

During the In2Track projects, the system was developed, adjusted and prepared for live track demonstration. Finally, during In2Track3, a 50 m demonstrator was installed at Gransjö, on the Swedish Iron Ore Line, and its structural and functional behaviour was monitored during a full year of operation.

Figure 62-3 Large boulders found during excavation (upper left), whole modules being positioned (upper right), pouring of levelling mortar (bottom left), finished track section at 96 hours (bottom right).

The installation, including dismantling of the track, excavation to base level and installation, was undergone in a 96-hour maintenance window despite unforeseen circumstances during the excavation phase, proving the potential for fast deployment thanks to precast components. To study the system performance, dynamic and structural monitoring arrays were deployed: accelerometers in rail, block and slab in three different sections provided input to monitor the absolute and relative movement of the different parts of the system, while strain gauges embedded in the concrete of 6 slabs and 10 blocks followed their structural response under load. The monitoring array allowed for remote gathering and processing of data. Thanks to the gathered and interpreted data, we are now in position to validate the system behaviour and its structural resilience under most dire circumstances: the Iron Ore line is subject to axle loads of up to 32 tons, and is with its location in the arctic exposed to temperatures as low as -50ºC.

Implementation and open questions

The 3MB system is ready for homologation in Sweden and launch to market. Additionally, structural data indicate the possibility of optimising geometry and reinforcement, reducing system height and lowering costs. A 30% reduction of slab and block height is under study.

The appearance of unexpected fissures in the blocks requires further study, addressing causes, foreseeable consequences and solutions. Investigation is already ongoing.

Finally, work is ongoing for the adaptation of the system for metro and urban railway infrastructure, with plans for a longer demonstration section in the coming.

Deliverable(s): D3.2 and D3.4

63 Shift2Rail turnout demonstrator

Christian Ebner-Mürzl, *voestalpine Railway Systems*, Michael Sehner, *Getzner*

Background

Considering the whole life cycle, the maintenance and repair costs of a turnout play at least the same importance as the manufacturing costs. They include switch inspection, component replacement, as well as maintenance costs including higher operating costs due to reduced availability.

At the beginning of the "maintenance-optimised turnout" project, a comprehensive cost analysis was carried out based on data from ÖBB Infrastructure. This shows that, in addition to costs for replacing the crossing and replacing the half switch device, cleaning the ballast is a key cost factor over the life cycle of a turnout. Ballast cleaning is typically necessary once in the lifespan of a turnout, since dynamic loads and higher settlement rates in the turnout cause ballast destruction. During this process the fine-grain proportion of the ballast is increased and as a result track geometry can no longer be sustained without frequent tamping. The direct costs for tamping are relatively small, but it also causes operational difficulties, which is why a holistic optimisation of the turnout in terms of robustness against changes in track geometry was considered sensible.

Increased knowledge and implementable results

As part of the project, a new type of turnout – referred to as a "Shift2Rail Demonstrator Turnout" – was developed and produced in order to reduce maintenance and repair costs.

To improve the service life and reliability of the switch device, switch rails made from 400 UHC® HSH® rail material are used in the form of the asymmetrical, self-detecting switch rail profile 60E1A-SD. The special TOZ+ switch rail machining ensures a high wear reserve in the critical area of the first lateral contact between wheel and switch rail. The higher wear reserve results in greater resistance to cracking and switch rail breakouts.

The switch rail profile 60E1A-SD is a new profile shape with increased lateral rigidity. During development, the rail head and rail height were adopted from the standard profile shape 60E1A1, but the switch rail base was made 25 mm wider. This increases the lateral rigidity of the switch device and improves the ability of the actuating system to detect trapped. foreign bodies. This leads to a lower sensitivity to interference and thus to an increase in the availability of the switch . With the ÖBB switch designs, the number of end position testers for position monitoring could be significantly reduced by using the reinforced switch rail profile. The zentrak SCM is installed in the switch drive to monitor the condition of the control system.

In the crossing area, as well as in the transition zone from long sleepers to short sleepers, the ends of the sleepers were widened from 300 mm to 350 mm, to reduce the pressure between sleeper and ballast, thereby reducing ballast destruction. For further improvement of ballast contact properties, ends of the short sleepers of the two diverging tracks were coupled with an elastic sleeper coupling, which allows forces to be transferred into the other track.

The ERL NG fastening system was developed to achieve the desired elasticities in the rail and crossing area. This system allows a high variability of vertical stiffness while the tilting resistance of the rail remains high. Optimising the Sylodyn® base plate pads resulted in an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optimised nominal stiffness of 25 kN/mm in the frog area and 60 kN/mm in the check rail plate area By adjusting the intermediate plate stiffness beneath the frog area alone, a 10% reduction in static ballast pressure was achieved. This additional elastic layer was matched to the polyurethane under sleeper pads which are already a standard for turnouts at ÖBB.

Implementation and open questions

As part of the EU project Shift2Rail, it was possible to calculate, develop, simulate, implement, measure and demonstrate many maintenance-relevant improvements in one turnout for the ÖBB as track operator. The collaboration between voestalpine Railway Systems, Getzner Werkstoffe, Kirchdorfer Concrete Solutions, ÖBB Infrastructure and the scientific partners Materials Center Leoben, Chalmers university and Virtual Vehicle Research was fruitful.

Measurements of the pressure between sleepers and ballast were performed with the innovative SMART Sensor Sleeper Technology from Getzner. A significant reduction in forces (-49% to -69%) and a reduction of ballast contact pressure of around 30% was achieved in the frog area. This should result in less ballast abrasion and broken ballast.

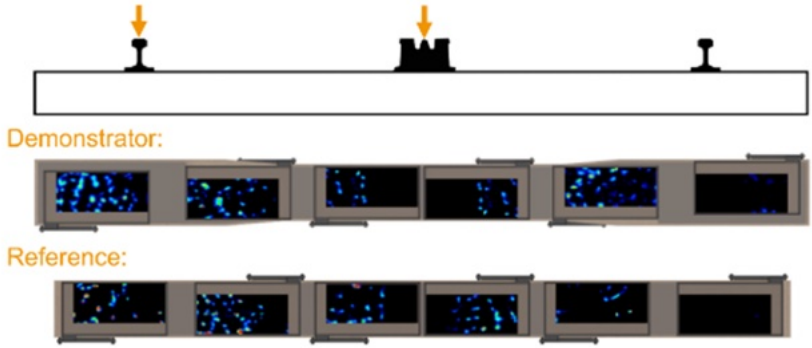


Figure 63-1 Pressure distribution under sleeper beneath frog tip

The measures in the tongue with the introduction of the 400 UHC HSH® rail quality with TOZ+ machining also addresses the need for longer component lifetime and thus lower maintenance requirements.

The measurement campaign generated a lot of data that can be used in research beyond the immediate validation of new turnouts. For example, it has already been used to calibrate a switch model from Chalmers University of Technology. Analysis currently taking place suggest further useful findings.

Deliverable(s): D1.3

Photo: voestalpine Rail Technology

64 Rail track tests

Norbert Frank, *voestalpine Rail Technology*

Background

A lot of contributions to all three In2Track projects show that modelling and simulation are used in development and evaluation of improved and new products and technologies. They allow to study the influence of various parameters on the product performance in a much shorter time frame as compared to any real site testing. This does not mean that such tests become obsolete – but it changes their role from pure observations at selected high stressed locations to input for validation and verification at well controlled and monitored conditions.

In addition, the improvement in performance of rails against wear and rolling contact fatigue increases the time needed for track testing from a few years to more than a decade. The aim is to combine results from short time laboratory tests with track tests of only 2 to 3 years in the numeric evaluation, allowing extrapolation to the entire life cycle of rail and track. This concept of whole system modelling and hybrid testing methodology is explained in chapter 15 Reduced environmental footprint, in detail.

The four rail demonstrators used in the In2Track projects have a simple setup using today's best rail and a new rail steel installed in the same curve for a direct comparison.

Two demonstrators featuring grooved rails were installed at Wiener Linien's urban tracks. Tight curves were chosen to study the development of wear in a comparison of two heat treated steel grades with different hardness.

Two other demonstrators of voestalpine Rail Technology focus on damage by head-checking in curves. These are shallow rolling contact fatigue cracks along the gauge corner of the rail, developing by the local slip and creepage forces in curves of approximately 1000 m to 3000 m radius. The appearance and growth of head checks can be controlled by maintenance, i.e., by removal of the fatigued and cracked surface layer. This is a large cost driver.

Increased knowledge and implementable results

The two demonstrators of the grooved rail tracks featured curve radii of approximately 25 m to 35 m. Wear on the gauge face of the outer rail is the limiting factor and requires rail replacement or restoration of the worn area by deposit welding. Both actions are very costly and might include slow orders as well as track interruption of a tramway line that operates every 3 to 5 minutes. The vehicles were tramways with classical rigid axle bogies as well as with single wheel suspensions. The comparison was between the regularly used steel grade R290GHT and the innovative high-strength rail steel grade 400GHT® – the numbers reflect the hardness in the rail head area.

Table 64-1 Improvements of 400GHT® vs. R290GHT

Abrasive wear	Side wear [mm]	Vertical wear [mm]
R290GHT	6,5	9,9
400GHT®	3,3	2,0
Wear ratio 400GHT® to R290GHT	50%	20%

While Table 64.1 shows the wear relations, a life cycle model gives a better idea of the practical impact of the 400GHT® rail steel. The LCC model was supported by the whole system modelling of the project partner Virtual Vehicle. It was the first time that a grooved rail track was simulated in a whole system model.

Results suggest that the 400GHT® grooved rail can be used for more than 20 years in this curve without any need for gauge corner repair welding, while the R290GHT rail needs several gauge corner repairs and at least on replacement.

Figure 64-1 Life Cycle prognosis based on linear wear models.

The two other demonstrators were done at mixed traffic conditions in Vignole rail tracks at Trafikverket TRV in the south of Sweden and the Hungarian MÁV network. The curve radius was approx. 1000 m, the annual load was 21 MGT at MÁV and twice as high as at TRV. The reference rails were R260 for TRV and R350HT for MÁV.

The material loss at the gauge corner corresponds to a wear rate on the order of 1 mm/ 100 MBGT, but with absolute values of approx. 0,5 mm for R350HT, 1 mm for R260, and a bainitic rail grade in between. These values are too small to allow for a reliable comparison. In contrast to the reference grades R260 and R350HT, respectively, the newly developed bainitic rail steel 340 Dobain® HSH® did not show any head checking during the 3 years of monitoring, giving no need for rail machining to remove the fatigued surface layer.

Implementation and open questions

The grooved rail steel tests were very important for a first and unique validation of the Whole system model in a complex environment.

The test with the bainitic Vignole rails shows that it is still difficult to come to reliable conclusions during a reasonably short track testing time. Modelling and combining such test results with laboratory testing must be enforced in the future to provide a short Time-to-Market for any new railway product.

Deliverable(s): D3.3

65 Three different SNCF-R optimised cast manganese frogs

Vincent Peyronnet, *SNCF Réseau*

Background

Cast manganese frogs are widely used in switches and crossings for their performance. However, the number of replacements of cracked frogs increased in the last years on the French network. These cracks initiated in the foot flange area of cast crossings (frogs), particularly on certain models.

A cracked frog can result in traffic slowdowns, at worst a rupture (and therefore potential derailment) and disruption to production ("emergency" replacement, as opposed to planned replacement). Today, we "treat" the problem by monitoring these crossings more closely and renewing them more frequently than average.

Figure 65-1 Common crossing cracked in the foot flange area (crack in yellow)

Increased knowledge and implementable results

Based on numerical simulation models, it was understood that crack initiation was induced by stress concentration zones in the foot flange area that cause stresses that exceed the fatigue limit of the manganese steel material (value determined in In2Track2).

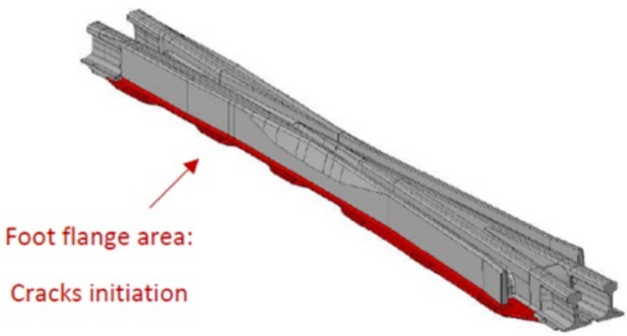


Figure 65-2 Foot flange area of the frog

Minor modifications to the frog geometry (compatible with manufacturing constraints) resolved these stress concentration problems. Numerical simulation models and topological optimisation approaches developed were transferable to other models of frogs.

This optimisation work is not justified for all frogs because the performance of some is already satisfactory (which explains the finding that only certain models of frogs are affected by these cracks in the foot flange area).

Implementation and open questions

This optimisation method has been applied to three frogs, with a fourth planned for 2024. The difficulty comes from the change in frog type, with the need to develop a numerical model for dynamic train transition of the crossing with the specific type of frog.

Furthermore, this model has historically focused on stress concentrations in the foot flange area, mainly due to the computational load required to carry out these simulations on the entire frog. However, foot flange area cracks are only one of the pathologies that can affect cast manganese frogs.

This method could be used to optimise other parts of the frog geometry, typically the internal structure. But this is more a matter for the manufacturing company.

SNCF RESEAU is ready to share its know-how in topological frog optimisation with interested parties, whether IMs or industrialists.

Deliverable(s): D1.3

66 SNCF-R cast manganese frog with welded bainitic rails

Nicolas Patteeuw, *SNCF Réseau*

Background

Several cracks of welding at the interface between rail ends and crossings occurred in the past few years on the French railway.

The current welding procedures of SNCF Réseau's suppliers of cast manganese crossing do not comply with the European welding standard and have lead to fractures.

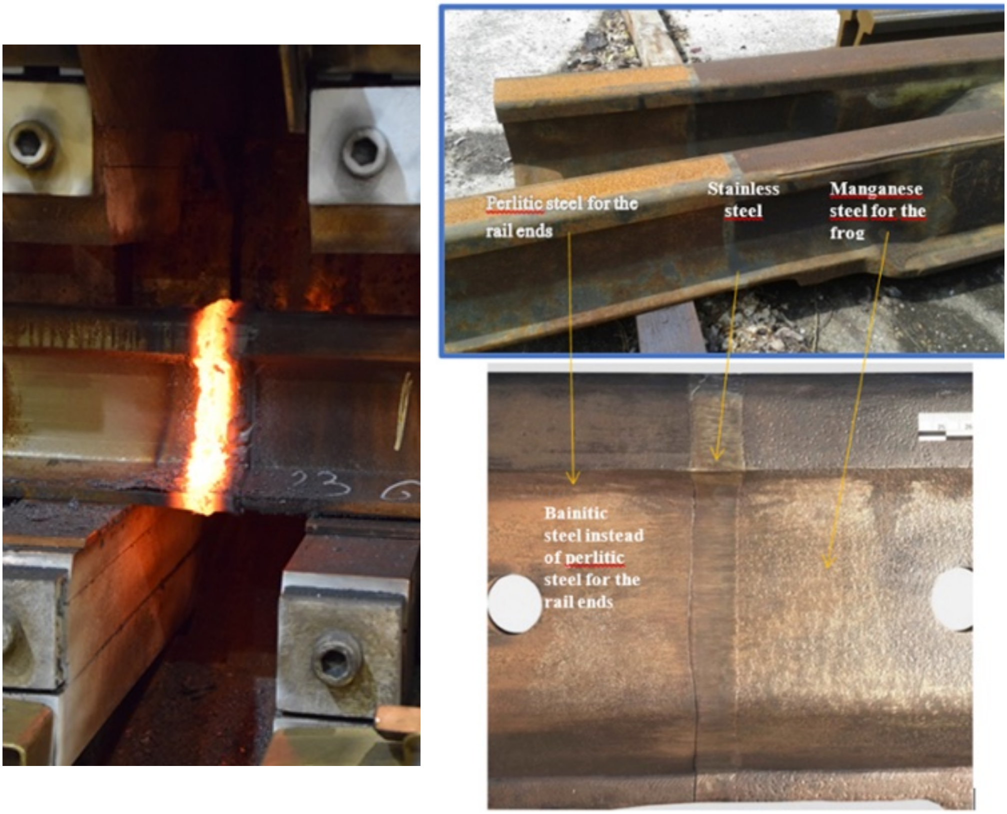


Figure 66-1 Welding, and rail ends

In order to reduce the cracks at interface between rail ends and crossings, this project aimed at:

- on one hand develop an innovative welding process for rail ends by replacing standard rail steel (perlitic steel) by bainitic steel.
- on the other hand, ensure that this welding process complies with European standards.

Increased knowledge and implementable results

After lab testing and validation in In2Track2, a demonstrator on track was necessary. To this end, a cast manganese crossing with bainitic steel rail ends has been installed in Narbonne, in the south of France in March 2022.

Four inspections have been made in one year to check the welds, with measurements of two parameters on each rail end: geometry (vertical straightness on the running surface) and hardness. Visual inspections have also been made each time.

No vertical collapse has been observed on the running surface. About the hardness, the measurements showed a small constant increase, but no cracks, creep or wear have been visually observed during the monitoring period of 12 months.

The welding of bainitic steel rail ends to cast manganese frogs showed satisfying results after one year on exploited track.

However, we know that more time is needed to carry out measurements on track. Indeed, welding defects could appear after 15 years of use. Fatigue tests will therefore have to be performed to evaluate the performance of these welds and the result will be compared to the welds made with the current process.

Implementation and open questions

Fatigue tests must be carried out on 15 welds in 2024, to assess the performance of these welds and to homologate this new process of welding.

Deliverable(s): D1.3

67 Airborne photogrammetry

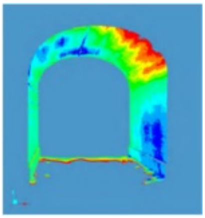
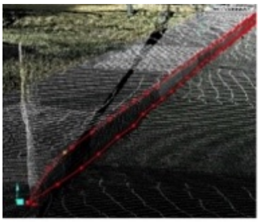
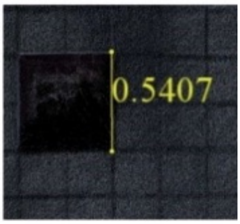
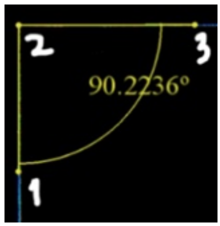
Tom Brodrick, *Network Rail*

Background

The primary objectives of this airborne photogrammetry study were to create digital models of bridges, establish guidance for their usage, and quantify the accuracy of the acquired data. The study aimed to harness technology for developing digital twins of existing bridges and detecting changes in their conditions over time. The project focused on utilising emerging surveying methods, specifically aerial photos captured by unmanned aerial vehicles (UAV) and Terrestrial Laser Scanning for masonry bridges. The survey covered five masonry and one concrete structure at various points in time. The project also sought to develop an approach for detailed examination processes by exploring techniques to analyse point cloud datasets to identify defects such as bulging, displacement, and crack propagation in masonry structures.

The study identified suitable analysis techniques, including surface analysis, edge detection, contour generation, measuring distance, and measuring angle. The selected software, 'CloudCompare,' was chosen for its ability to compare dense 3D point clouds, supporting defect detection in masonry.

Table 67-1 Analysis Techniques

			
Surface Analysis	Edge detection/ contour generation	Measuring distance between two points	Measuring angle created with three points

Increased knowledge and implementable results

Data preparation (Step 1): To prepare clean point cloud data for efficient analysis excess information, including grounds and surrounding environments, was removed. The approach significantly reduced file size and computing resource requirements.

Data analysis (Step 2): Single-scan analysis involved comparing the point cloud with a reference surface or an ideal 3D CAD mesh model. Two-scan analysis included cloud-to-cloud distance measurements and cloud-to-mesh comparisons between two scans captured at different times.

Result evaluation (Step 3): The evaluation process included the detection of spalling, bulging, loss of section, cracks, joints, and other defects. The accuracy of measurements was highlighted as sensitive to the quality of registration. For two-scan scenarios, the project recommended segmenting the bridge to improve accuracy and address missing data issues.

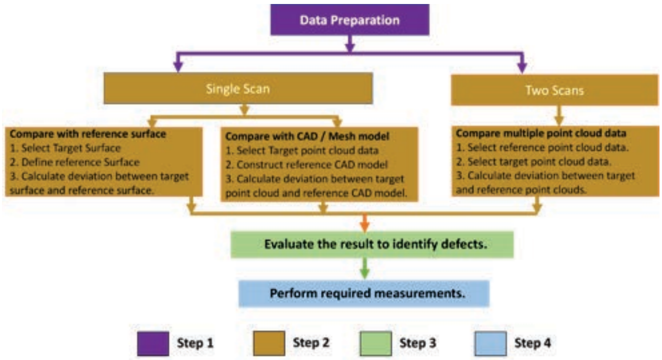


Figure 67-1 Flow chart of the methodology undertaken: Step 1- Data Preparation; Step 2- Data Analysis; Step 3- Results Evaluation; Step 4- Perform Required Measurements

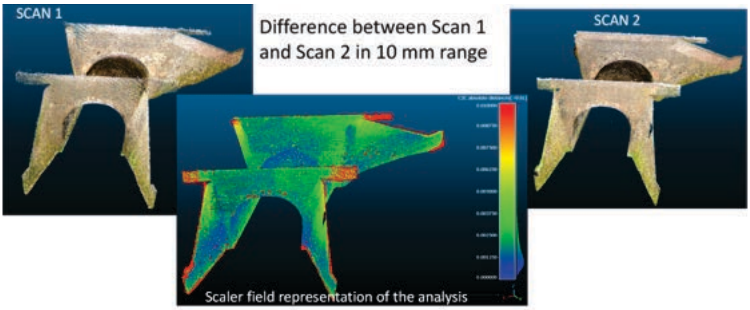


Figure 67-2 Comparison between two point-cloud data sets of the same bridge captured at different time steps

Implementation, Open Questions and Remaining Research

The project successfully demonstrated the practical application of point cloud data analysis for detailed examination of masonry bridges, effectively detecting common defects like spalling, bulging, cracks, and joint defects with required accuracy. However, to enhance efficiency, automation through plugins is needed for the analysis method currently reliant on CloudCompare. While CloudCompare proved effective, a custom tool tailored is suggested for masonry bridge analysis to optimise performance and address specific needs. The project identifies accuracy dependencies, emphasising the crucial role of registration processes and model generation accuracy in cloud-to-cloud and cloud-to-mesh distance calculations, necessitating further research. Additionally, noise reduction challenges are highlighted for enhanced accuracy and reduced memory consumption, urging exploration of advanced methods, particularly for two-scan scenarios and larger datasets. Concerns are raised regarding software interoperability for dedicated tools, suggesting the need for future research on integration with existing ecosystems. Furthermore, optimising memory usage is essential for efficient processing of larger datasets, calling for ongoing research.

In conclusion, while the immediate focus is on implementing automated tools and dedicated software, open questions indicate areas for future research to enhance accuracy, efficiency, and applicability in masonry bridge inspection using point cloud data.

Deliverable(s): D5.4

68 Long-term monitoring of a railway bridge

Andreas Andersson, Raid Karoumi, *Royal Institute of Technology / Trafikverket*

Background

Railway bridges may experience large vibrations from passing trains if the load frequency of the train coincides with the natural frequency of the bridge. For long and slender bridges on high-speed lines this may occur within the range of the operational train speed. In combination with low inherent damping of the bridge, excessive vibrations during train passage may pose both a safety risk and riding comfort issues. This is usually accounted for in the design of new bridges but may be a concern when upgrading existing railway lines to higher speeds.

In addition, for long bridges with continuously welded rails, differential displacement between the track and the bridge end may result in excessive rail stresses. The rail stresses may be reduced by installing expansion devices in the track but results in increased cost for investment and maintenance.

The objective within In2Track3 was to explore methods that would result in more cost-efficient railway bridges, focusing mainly on dynamic effects but also on longitudinal track-bridge interaction. Within In2Track2, an existing railway bridge susceptible to dynamic excitation from passing trains was identified and a system with retrofitted external dampers was developed to improve the dynamic performance. Within In2Track3, a long-term monitoring system was installed to verify the performance of the bridge with the dampers and to study seasonal variation due to temperature in both the rail and the bridge.

The retrofitted damper system serves as a demonstrator that can be used on similar bridges, both to upgrade existing lines to higher speeds, and to optimise the design of new bridges. The data from the long-term monitoring system can be used in reliability-based assessment to ensure a more consistent safety format for dynamic effects on railway bridges. The current assessment for the need of rail expansion devices may also be improved.

Increased knowledge and implementable results

The case study bridge is a 48 m long simply supported single track steel–concrete composite bridge, illustrated in the figure below. The bridge was selected as the best candidate based on theoretical analyses of a large set of bridges and practical accessibility for testing and implementation.

The optimal position of the dampers was based both on the expected performance and access for installation. To avoid obstructing the area under the bridge, the dampers were installed horizontally at the roller support. In this case, the displacement experienced by the dampers is mainly a result of the vertical deflection of the bridge in combination with the vertical distance between the neutral axis and the roller support. The peak displacement along the damper is merely 2 mm during train passage, requiring high precision installation to avoid gaps in both the fasteners and the dampers. The near support installation resulted in a robust solution with few auxiliary components.

The dynamic performance of the bridge was verified by experimental testing before designing the dampers. In a second step the performance of the dampers was tested in the laboratory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under expected operating conditions. The first experimental testing after installing the dampers on the bridge did not show the expected improvement in bridge performance. The cause was due to small gaps both in the fastening system and internally in the dampers. The remedy was to pre-load the fastening with additional washers and to create an over-pressure in the damper fluid by externally retrofitted accumulators. Additional experimental testing was performed and showed the expected improvement in the bridge response. A long-term monitoring system was installed to monitor both the bridge, the dampers and later also the rail. A higher natural frequency was observed during winter, but the dampers are still providing sufficient additional damping.

Figure 68-1 Top: view of the bridge during passage of an X62 train, bottom: details of the retrofitted damper near the roller support.

Implementation and open questions

The use of external viscous dampers to improve the dynamic performance of a railway bridge was successfully demonstrated using both simulations and full-scale testing. The performance has been studied with a long-term monitoring system since June 2021, both to assure that the system is still working as expected and assessing the seasonal variation. Given the current trains and operating speeds, the current limit criteria for dynamic performance would be met even without dampers. It is therefore suggested that the dampers are dismounted but the monitoring continues to collect more data of the bridge without the dampers. Also, more data regarding the longitudinal track–bridge interaction is needed.

The demonstrated damper system is seen as a cost-efficient solution with few components that can improve the performance of similar bridges, both in design of new bridges and improving the performance of existing bridges. What remains is to determine a suitable maintenance or inspection plan of the dampers, as well as the total life cycle cost.

Deliverable(s): D5.6

69 Sub-surface inspections in tunnels

Andrew Brown, *Network Rail*

Background

The examination of brick-lined tunnels, dating back to the Victorian era (circa 1840-1850), relies on visual and tactile inspections. To ensure structural integrity visual inspections from track level and detailed tactile examinations of the tunnel lining are carried out. Due to their age, little is understood about the changing condition in and behind the brick lining. Hollow-sounding areas identified through tapping the lining during examinations, indicate potential issues i.e. ring separation within the brickwork that has resulted from mortar degradation and can cause possible structural instability and detecting ring separation is subjective. Network Rail has explored using Ground Penetrating Radar (GPR) to detect sub-surface defects, although the results vary due to geological conditions and complex interpretations. The advancements made in GPR technology made in this project, allow detailed 3D subsurface models, improving our understanding of risks posed by ageing tunnels. Improved GPR capability promises more accurate identification of sub-surface defects, addressing subjective defect identification. This enhances tunnel examination methodologies, offering a precise assessment of associated risks. The shift toward advanced 3D GPR technology, termed Tunnel Sub-surface Inspection Radar (TSIR) developed with Quantum Structures (UK), signifies a promising step in tunnel safety management.

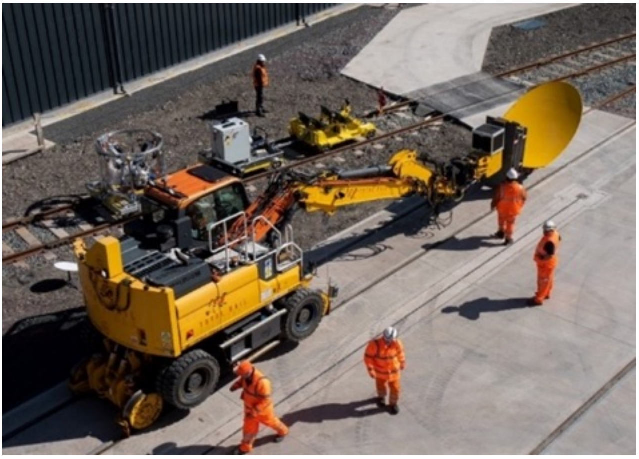


Figure 69-1 Tunnel sub-surface inspection radar mounted on a road rail vehicle

Increased knowledge and implementable results

Significant subsurface imaging has been achieved with the section size of the tunnel linings being easily identified and also the geotechnical interface, with the most significant advancement being the identification and imaging of hidden defects. The results show that the system can reconstruct images of a tunnel's subsurface, identifying features and substructure defects and assets, voiding and ring separation, allowing tunnel engineers to accurately identify areas for more in-depth inspection and evaluation, ultimately allowing more targeted interventions. An example of a GPR image in the lateral image plane is given in figure 69-2. This data set can then be sliced into planes as shown in figure 69-3. The results shown illustrate the efficacy of the TSIR system. Discontinuities within the subsurface of the tunnel can clearly be seen. The discontinuity labelled in figure 69-3 corresponds with a known issue in Alfreton tunnel, a suspected shaft. The other discontinuities indicate areas where previously unknown anomalies could exist. Very dark areas indicate a large difference in refractive index across an interface indicative of a void as the refractive index difference between masonry and the ground is not as large. These examples show that the system can detect subsurface features within tunnel substructure that could be indicative of defects.

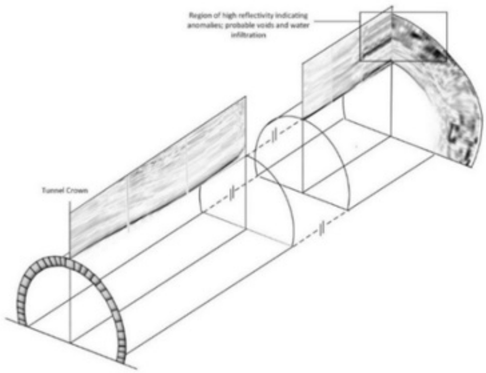


Figure 69-2 3D Cross section of Alfreton Old Tunnel, 2023

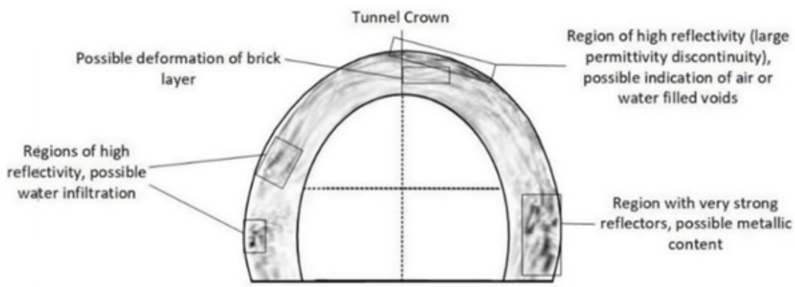


Figure 69-3 A cross section of the tunnel lining using B-scan data from Alfreton Tunnel

Implementation and open questions

Now that the TSIR technology has been proven, the system will undergo further development to comprehend the characteristics of the anomalies identified by TSIR. This necessitates employing ground investigation techniques to enable comparative analysis. After a competent consultant conducted an assurance report on TSIR, which provided positive feedback, further development is now underway including: Creating user-friendly viewing software, enhancing TSIR equipment to be more compact with improvements in post-processing and formulating a technical roadmap to ensure the full potential is achieved.

Deliverable(s): D5.3

Photos: Sinem Tola, Joaquim Tinoco, NetworkRail, Fugro

70 Scour monitoring from train-induced vibrations

Joaquim Tinoco, Sinem Tola, José Matos; *University of Minho*

Background

Bridges with piers in rivers are at risk of foundation scour. Structural parts in the river cause turbulence around these piers, which leads to soil erosion – known as local scour. The time required for the erosion depends on the soil type around the bridge foundations. For instance, shale and silt soil around a foundation can be swept away after a single storm, whereas a bedrock scour requires hundreds of years to form. Scour is a leading cause of bridge collapse; therefore, rapid detection is crucial. Underwater inspection is one of the most widely used techniques for detecting scour. Equipment-based underwater inspections include radars, sonar, and lasers, which are expensive solutions. Diving is a commonly utilised approach, but it poses significant risks, and visual examination may not always identify all damage. Therefore, scour monitoring presents itself as a helpful alternative. Direct structural monitoring involves using sensors installed in the bridges to record parameters such as accelerations, displacements, velocities, strains, etc. The data collected from these sensors is analysed using numerical techniques such as frequency domain analysis, Hilbert transforms, and mode shape derivations. This analysis provides information indicating the extent of scour damage to the structure. Alternatively, an indirect monitoring method involving sensors on passing vehicles is more cost-effective as it requires fewer sensors. This technique removes any possible service disruption when orienting direct structural health sensors on the bridge. The study's main objective was to detect scour on a railway bridge using displacement signals obtained from Fugro's RILA (Rail Infrastructure Alignment Acquisition System in figure 70-1) sensor unit that can be coupled with any train in minutes.

Figure 70-1 RILA (by Fugro) was implemented on the train.

Increased knowledge and implementable results

A finite element model using Moving Reference Influence Lines was created to simulate a RILA instrumented train passing over a bridge. An off-bridge, track-only model was also generated to account for poor ground conditions and calibrate the model. Sixteen healthy stage runs of the Carlisle WCM1/5 bridge proved sufficient for modelling the WCM1/5 Carlisle bridge in the UK. RILA runs were classified into four clusters based on the movement direction of the train and RILA orientation, positioned at the back or front of the train. In the case of RILA-trailing measurements, recorded at the back of the train, discrepancies were detected in the displacement measurements at pier locations. Speed interpretations and frequency domain analysis were conducted to investigate this discrepancy. Various simulations were carried out with differently weighted trains, and the relationship between the train's centre of gravity and the location of the measurement unit was investigated. However, none of these analyses yielded a significant result, leading to the assumption that the difference was due to GPS errors.

Owing to the absence of RILA displacement data during the scoured period, the method for detecting scour using in-service measurements could not be verified entirely with field measurements. Instead, scoured period displacements had to be synthetically generated with a dynamic code considering vehicle bridge interaction. Each simulation has random velocity and train body weight to mimic more accurate measurements. The difference between the healthy and 20% scoured stage pier stiffnesses was computed using a cross-entropy optimisation algorithm that minimised the difference between the numerical model and the measurements/ simulations that functioned as scour indicators. When RILA is implemented at the front of the train, the optimised scoured pier stiffness is 89% of the healthy pier stiffness. In contrast, RILA is implemented at the back of the train, and scoured pier stiffness is optimised at 87% of the healthy pier stiffness.

Implementation and open questions

Owing to the lack of scoured period measurements, the case study had to be partly completed using artificially generated simulations. While only relating to the healthy case, the field data is helpful as it shows repeatability and indicates the resolution and accuracy. Based on the case study's findings, it is highly probable that the proposed scour detection method could be validated using data from another bridge featuring RILA displacement measurements at both healthy and damaged stages. In further studies, the scour identification procedure could be repeated with sufficient measurements, including both damaged and healthy stages. The RILA displacement data combines the inertial measurement unit and lasers, providing some information related to the bridge response. However, it should be noted that the RILA displacement measurements include differences from the bridge displacement responses simulated by a realistic dynamic model. It is assumed that the accelerations of the RILA unit itself, as captured by the Inertial Measurement Unit, contribute to the measurements by causing non-periodic effects and additional magnitudes that cannot be accounted for in simulations. Moreover, the field measurements of a research paper focused on RILA indicate that the discrepancies between the loaded (measurement point close to axle) and unloaded measurements (measurement point far from axle) are unevenly distributed. This may also contribute to the non-periodic trend in the RILA measurements. Therefore, this research does not aim to calculate definite pier stiffnesses. Instead, it reveals a difference between optimised pier stiffness values of healthy and damaged bridge stages, indicating scour. To extend the approach to the network level and increase the confidence of the proposed methodology, hundreds of RILA-implemented vehicle crossings have been simulated with bridges of varying span lengths/span numbers to train an artificial neural network (ANN). As an ongoing study, this classification ANN model has been developed to predict the presence and location of the scour.

Deliverable(s): D5.4

71 Detection of rail surface defects based on axle box acceleration measurements

Wassamon Phusakulkajorn, Jurjen Hendriks, Jan Moraal, Chen Shen, Yuanchen Zeng, Siwarak Unsiwilai, Bojan Bogojevic, Alfredo Nunez, Rolf Dollevoet, and Zili Li, *TU Delft / ProRail*, Matthias Asplund, *Trafikverket,* Arjen Zoeteman, *ProRail*

Background

Inefficient management of rail surface defects can increase maintenance costs, safety hazards, service disruptions, and catastrophic failures like rail breaks. To achieve adequate management, having effective technology capable of timely detecting and frequently monitoring rail defects is of utmost importance. The aim is early detection of defects to maintain safety levels and prevent the re-appearance due to residual damages.

Figure 71-1 The installed ABA system

Various measurement technologies, such as visual inspections, geometry profile measurements, and other measurement techniques, have been used for the detection of rail defects. While these methods provide insights, they often lack the capability for early-stage defect detection. Thus, most of these technologies are suitable for reactive maintenance since they detect defects when they reach a certain severity level. Axle box acceleration (ABA) technology provides a solution capable of frequent monitoring, mounted on trains in operation without dedicated measurement vehicles (see figure 71-1). Its basic principle is to use a train as a moving load that excites the infrastructure and to detect defects by evaluating the time-frequency characteristics of the dynamic response measured by accelerometers installed on axle boxes of the train. ABA systems have shown promise in detecting defects in the early stages. However, its widespread application and need for robustness require further validation and development. This work presents the results of detecting and monitoring rail surface defects using ABA technology.

Increased knowledge and implementable results

Figure 71-2 The measured locations

Extensive measurement and validation campaigns were conducted along the Iron Ore line between Sweden and Norway (see figure 71-2). This line is mostly single-track with passenger–freight mixed traffic and heavy axle load (up to 31 t). The measurement train ran two round trips along the line for approximately 400 km and analysed ABA data almost in real-time for rail defect detection. No prior information about the location of defects and the type and location of railway assets was required. This campaign used the ABA measurements from the vertical and longitudinal directions to detect rail defects, including squats. The high sampling frequency of 25.6 kHz was also considered to capture the characteristics of small defects in their early development.

Photo: Siwarak Unsiwilai

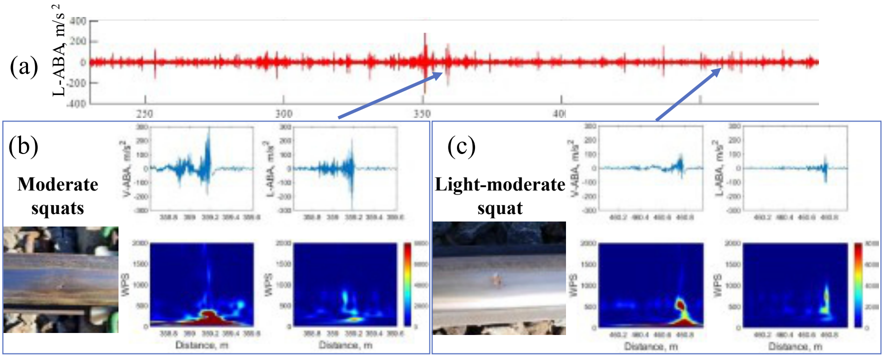


Figure 71-3 Example of the ABA measurements of a rail portion from Location 1

By analysing data acquired from the accelerometers in vertical and longitudinal directions, the locations of rail defects are determined based on the variations of the obtained ABA energy. Figure 71-3 illustrates an example of the ABA measurements in which relatively high energy is observed in the signal. In accordance with the Dutch definition, squats refer to localised rail head deformation, initially without visible cracks. Squats are classified into three classes based on their visual size – light, moderate, and severe. The localised deformation causes an impact, progressing into moderate and severe squats, characterised by a V or U-shape during their moderate and severe stages. Illustratively, figure 71-3(b) demonstrates the ABA energy at a location corresponding to a moderate squat, while figure 71-3(c) depicts that of a light-moderate squat. These rail defects, including squats, are detected using an outlier detection approach (detecting energy variations beyond local average values). According to our validated sections, 100% of rail defects were detected using time-frequency analysis and an outlier detection approach. This shows the capability of ABA technology for the detection of rail defects. The methodology also allows for identifying priority locations such as defective welds, joints, transition zones, etc. Its use for prescriptive maintenance recommendations is being explored in the framework of the IAM4RAIL project.

After the initial ABA measurement, subsequent measurements of defects and track components update their conditions, allowing for assessing their growth rate. These measurements reveal early defects and help evaluate maintenance effectiveness, e.g., determining the required grinding depth for specific defect severity.

Implementation and open questions

The effectiveness of ABA technology for the detection and monitoring of rail surface defects will lead to integrating ABA technology into existing railway track information systems, enabling continuous monitoring of the ABA energy at critical locations such as welds, S&Cs, insulated joints, transition zones, bridges, etc. Further research and development include extracting and integrating information from diverse data types related to railway assets and defects to synergise with the physical understanding of the ABA signals. Then, the integrated information can enhance the effectiveness and interpretability of continuous monitoring, revealing new insights into defect progression, maintenance requirements, and the overall condition of the railway infrastructure.

Deliverable(s): D3.4

72 Rail eye friction level sensor

Johan Casselgren, *Luleå University of Technology*

Background

The friction between the wheels and the rail is an important parameter considering for example rail fatigue. Measuring contamination on the railhead and translating that to a general friction level using an optical sensor could give information regarding the status of the rail. If a measure of the friction level could be obtained continuously with a sensor mounted on a train. It would enable a map presentation of track status regarding friction level.

Today, on some rails a friction modifier is applied to lower the friction to decrease fatigue when the axel load increase. Knowing how much, and especially if any friction modifier is present on the rail would decrease the fatigue of the rail especially in curves. Another example is when crushed leaves create low friction on the rail. Being able to measure this contaminant, preferable in real time, mainly helps to adjust breaking and traction to keep the wear on both wheel and rail to a minimum.

There is no product on the market for friction level estimation today that can give continuous measures, but research has shown that it is possible to distinguish different contaminants with optical sensors. But the optical sensors are not tested in real environments, which can be a problem as the environment is harsh. The Rail eye sensor is one of the prototype sensors that is built for friction level monitoring and is tested in this project mounted on a train to investigate the performance in a real environment.

Increased knowledge and implementable results

Figure 72-1 Mounting of friction level sensor on train.

The demonstration went well and although the sensor was mounted in an exposed position as shown in figure 72-1 the sensor worked well. The weather during the demonstration was snowy and rainy, so it was perfect to test the sensors performance in a harsh environment, see figure 72-2 left. The sensor detected a little lower friction as the rail head was wet. One thing that was shown during the test was that the sensor, that only measured in a small spot, could not measure the contact band of the rail head all the time. This is shown by the drops in the reflected light from the optical sensor just before 1000, at 2300, just before 3000 and at 4500 to the right in figure72-2. The cause is that the sensor measures outside the contact band where the rail is rusty. This was found to be happening in curves which is not good as this is where the fatigue is highest.

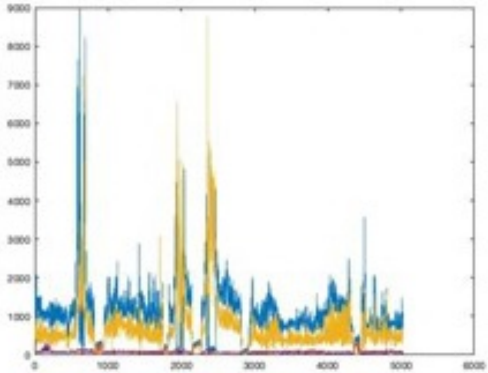


Figure 72-2 Friction sensor with slush (left). Signals from the friction sensor, measured during the test between Luleå and Boden (right).

Therefore, a second method using the same technology but another detector with a larger detection area covering the hole rail was tested. This laboratory test was successful, and the sensor could classify different contamination. But it also had the advantage to be able to estimate the width of the contact band at the same time as it could estimate the friction level according to table 72-1.

Table 72-1

Contaminant	Dry rail	Wet rail	LUB 90	Icy rail	Electro gel	Leaf
µ	0,7	0,6	0,35	0,2	0,5	0,1

Implementation and open questions

The next step for this research/demonstrator would be to test a new illumination solution for the detector with a larger detection area. This is started but not finished and not tested yet in real environment. As the illumination must be insensitive to surrounding light it is not trivial to move into a real environment. Similar techniques are developed for road and runways, so the interest regarding this research field is extensive but it needs to be explored further. The systems also need to be developed to endure harsh environments that moving vehicles are operating. This is also a focus for further work.

Deliverable(s): D3.4

73 ATMO urban grinding machine to reduce noise and vibration

Alejandro Salanova, *Plasser & Theurer*

Background

When looking at the generation of noise emissions from urban railways, engine and rolling noise are the main sources. Through grinding, the corrugation on the rails can be significantly reduced, and in some scenarios also eliminated which reduces rolling noise.

When preventing noise and vibrations, some measures are used to reduce the emissions: reducing the operating speed, installing noise barriers, conditioning of the rails, and — the most popular with infrastructure managers — rail grinding. The goal of rail grinding is to extend the operational life of the rails, reduce noise emissions and vibration impact to the environment. In contrast to mainline tracks, rail grinding in urban areas has some differences that are reflected in the design of the city grinding machine.

Figure 73-1 ATMO testing inside Wiener Linien facilities

The Plasser ATMO urban grinding machine was designed to work during regular operation, which means frequent acceleration and braking, working in short intervals, varying distances between stops, and moderate travel speed. It is also designed to work in small radii curves, and to be integrated as a towed trailer without self-propulsion. Therefore, it is flexible in choice of towing vehicle. It is also operated unmanned from the traction unit through a remote control. The machine incorporates two working methods: oscillating stone and sliding stone in both modes the vertical pressure can be adjusted.

Increased knowledge and implementable results

In In2Track2, indoor tests were performed in Wiener Linien's facilities in Vienna. Here the functionality of the machine with different parameters settings was tested and removal depths were established to be on average 0,011 mm.

Later in In2Track2 and in In2Track3, the machine was tested in the open network of the Wiener Linien. In this phase, grinding stones with different hardness were tested. The improvement of corrugation was assessed according to EN 13231-3, while comparing oscillating and sliding mode at speeds up to 30 km/h.

In figure 73-2 a comparison of results with different stones after 10 grinding cycles in removing corrugation is shown. The oscillating mode is found to be superior. Also, the MS stone, a softer stone shows better corrugation removal with up to 90% removal.

Photo: Plasser&Theurer

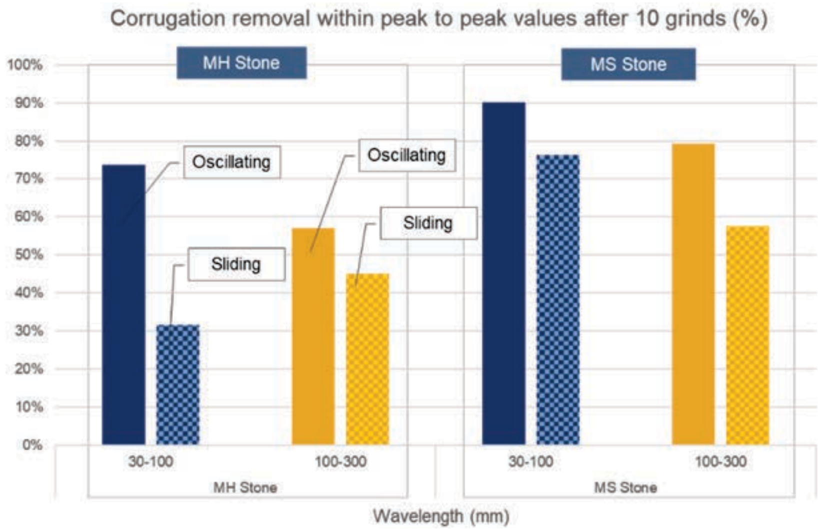


Figure 73-2 Corrugation removal with peak-to-peak values after 10 grinds in percentage

Rail roughness was measured before and after grinding together with sound and vibration emissions. These measurements were repeated after 3 weeks and revealed

- **Acoustic rail roughness:** Significant changes in values up to 15 dB reduction.
- **Vibration:** Significantly reduced by up to 50%.
- **Sound:** Emissions could be reduced up to 8dB in the Flexity tramway and for Ulf and ExCx tramways up to 4 dB.

Implementation and open questions

Regularly carrying out grinding on the tramway network can slow down the growth of corrugation, resulting in reduced noise and vibration emissions in the surrounding area. This positive effect on tram emissions increases the acceptance of rail-based public transport in urban areas, leading to fewer complaints from residents and less personnel effort required by the transport operator to manage these complaints. On the vehicular side, reduced vibration emissions lead to improved ride comfort and reduced strain on the vehicle's bearings and suspension components.

Within Shift2Rail, we managed to design and complete the construction of the Plasser ATMO urban grinding machine, proceeded with tests inside the facilities of Wiener Linien, to be followed by tests at their open network, both with very promising results. We analysed the machine's performance, the ground surface, and the improvement of corrugation of the rails, to be finalised with a test of the improvement of the noise and vibrations before and after operation, being a good prof of the benefits of using the machine.

In the short term, we want to make significant improvements in the machine, electrifying some components of the machine, and small design upgrades. We as Plasser & Theurer offer the machine as a service, and we are in contact with potential customers in order to manufacture more machines of this new line.

Deliverable(s): D3.3

Photo: Sergio Cavalaro, Andrew Brown

74 Replacement of damaged tunnel lining

Andrew Brown, *Network Rail*

Background

The vast majority of Network Rail tunnels are brick lined. This amounts to an area of circa 500,000 sqm of brick work. Large amounts of local areas of defective brickwork are repaired every year. Current methods of repair are time and resource hungry. The skill set necessary to carry out this type of repair is becoming more difficult to find. On average it takes two shifts of eight hours to complete one repair of 1sqm using a four-person team. Access is also difficult to acquire to carry out the repair, this often means that defects are left unmitigated until access can be gained.

Figure 74-1 Traditional method of undertaking tunnel brickwork repairs

From a tunnel portfolio level perspective, the rate of degradation commensurate with the rate of repairs means the current working practices to carry out repairs is unsustainable. New methods of repair that remove the need for highly skilled brick layers and high levels of access for small areas of lining are therefore necessary.

Increased knowledge and implementable results

To reduce the amount of time and the number of operatives required to carry out the repair, the process needs to efficiently:

- Inspect the defect to measure the volume of material required.
- Sample material in the affected area to ensure sympathetic replacement in terms of material characteristics.
- Re-produce the material to the correct characteristics.
- Install the material.
- Check the re-installed material's integrity.

The project looked to fulfil the following objectives:

- Identify the ideal state of the tunnel repair process.
- Determine whether the volume, position and orientation of a tunnel defect can be determined.
- Determine whether the composition of the removed material can be assessed to quantify the relevant material properties.
- Develop working prototype of a system to apply repair material to identified defects.

Following a lengthy down selection process, a process to carry out fast repairs was chosen using a quick set, two-part resin. Successful testing in the Loughborough University laboratories was carried out, to confirm the material properties, adhesion, etc. This was successful.

Temporary works to keep the material in situ during the repair was designed using a mechanical 'flexible plate' system. The plate is attached to a road rail vehicle (RRV) and can be adjusted to the curved shape of the tunnel using remotely controlled hydraulics (figure74-2).

Implementation and open questions

Following laboratory trials, demonstrations of the new patch repair system in a real tunnel environment occurred in two railway tunnels in the UK. The process of positioning the equipment was simulated at different positions inside the tunnel. Once the area for repair was prepared, the injection of the resin was successfully performed.

Regarding the time to carry out the repair; once the flexible plate was in position, the resin can be injected immediately through the plate. The rapid hardening resin only requires support for approximately ten minutes and the flexible plate could be removed. See figure 74-2.

Further work will see improvements to the pumping equipment to create a more compact and ergonomic design, also further material validation for fire compliance will need to be achieved.

Figure 74-2 The flexible plate for the demonstrator (a), detail of perimeter seal, (b) execution of the repair (c, d and e) and patch repair after removing flexible plate

Deliverable(s): D5.2

75 Fatigue capability improvement of bridges

Alfredo García Farré, *Acciona*

Background

In Europe, more than 70% of existing steel railway bridges are over 50 years old, and approximately 30% of them are over 100 years old. As European bridges age, renovation and rehabilitation tasks are becoming more crucial in the budgets and plans of companies that oversee railway line management. Hence, it is necessary to create new restoration methods that allow old railway bridges to meet current quality and safety standards, without resorting to cumbersome and costly restoration methods that might cause delays, interruptions, or other inconveniences for the end user.

Fatigue is often a major problem limiting the load-carrying capacity and the residual life of steel bridges. 90% of fatigue damage in steel bridges is caused by deformation-induced cracking, this type of fatigue damage is often the result of secondary restraining forces generated by unintentional or overlooked interaction between different elements in the bridge. In particular, the connections between longitudinal and transverse elements of the floor system of railway steel bridges might be critical with respect to fatigue due to these deformation-induced secondary forces.

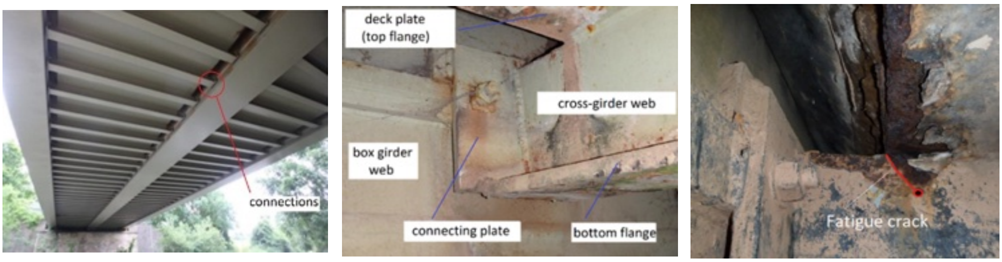


Figure 75-1 Detail of connection susceptible to fatigue cracking

Currently, mitigating these types of pathologies requires welding or bolting heavy steel plates that are susceptible to corrosion. This process is slow and sometimes necessitates temporarily closing of traffic on the bridge. In the case of very large cracks, it might even be necessary to replace the entire component.

Increased knowledge and implementable results

During the In2Track3 project, the possibility of reinforcing fatigue-prone points was investigated using carbon fibre angles (CFRP) directly bonded to the metal using epoxy adhesives. The aim was to develop a reinforcement system that was easy and quick to install, resistant to corrosion, and that wouldn't require interrupting rail traffic during reinforcement work.

To assess the reinforcement system, a full-scale demonstration was conducted on the Eastington Bridge railway bridge (UK). Four CFRP profiles were installed to reinforce two cross-girders. To monitor a potential onset and propagation of fatigue cracks in the reinforced profiles, the angles had an opening (60 x 30mm) in the critical zone allowing for the installation of strain rosettes, see figure 75-2. To compare fatigue accumulation with respect to unreinforced cross-girders, the adjacent girders were monitored. The system underwent monitoring for a year, and the results were then evaluated.

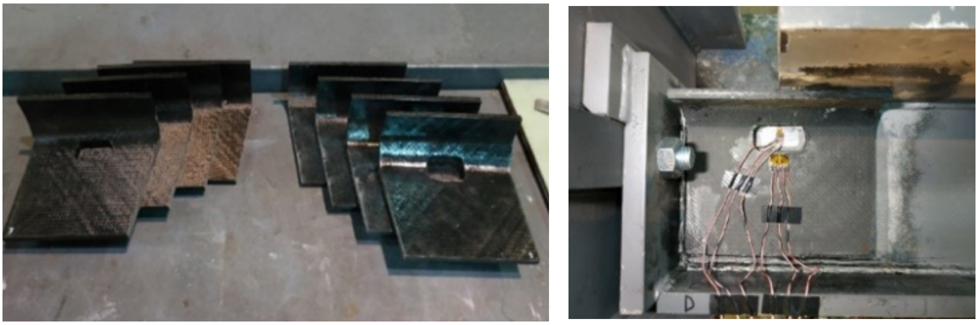


Figure 75-2 Detail of the strengthening CFRP angles.

During the monitoring period, it was observed that the accumulated fatigue in the core of the reinforced girders increased at a slower rate than the fatigue in the unreinforced girders.

The results indicate that the CFRP reinforcement effectively mitigated the accumulation of fatigue in the area studied. The reduction in fatigue accumulation is attributed to the improved load-sharing capability of the CFRP profiles, which are capable of bearing part of the stresses and reducing the load in the critical region.

Implementation and open questions

As bridges approach the end of their lifespan, it will be necessary to increase strengthening tasks on a large number of railway bridges across Europe. This new strengthening method offers an alternative to other slower or more intrusive methods. However, for its implementation to become a reality, it is still necessary to assess the durability of the bond between the CFRP angle and steel when exposed to environmental conditions. Additionally, it's crucial to evaluate the long-term behaviour of the adhesive under the frequent vibrations it will experience during its service life. These factors must be considered to ensure the continued effectiveness and safety of the CFRP reinforcement solution in the long term.

Deliverable(s): D5.4

76 Improved shear capacity of railway bridges

Alfredo García Farré: *Acciona*

Background

Concrete trough bridges are a standard bridge type that was widely built in Sweden and Finland from the 1950s, allowing a maximum axle loads of 250 kN. Today, as new railway lines are designed for higher loads, these structures need to be strengthened to increase their service lives. If the shear capacity of the bridge is not adequate to sustain the new loads, shear cracks may occur in the webs of the girders. Consequently, the steel reinforcement traversing these cracks is subjected to stress variations, which can cause bond failure and fatigue damage., ultimately leading to the need for bridge repairs.

The main drawback to develop an appropriate external shear strengthening system for concrete trough railway bridges is the inaccessibility to both sides of the main girders without disturbing traffic, as the centre of the section is covered with ballast. For this reason, the embedded through-section (ETS) technique, which consists of reinforcing bars inserted into holes bored through the cross section of the main girders and bonded with an epoxy adhesive, was found to be a promising technique to be studied in more detail during previous In2Track2 project. See figure 76-1.

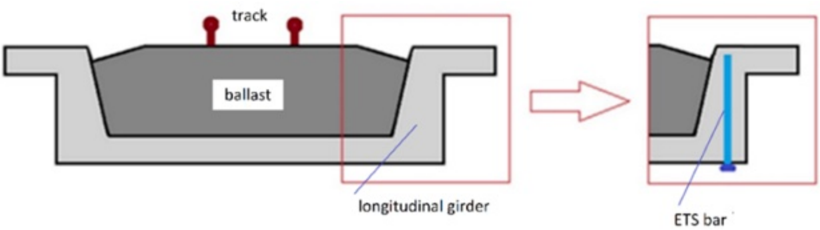


Figure 76-1 Detail of the strengthening technology by inserting carbon bars in the concrete structure.

Recent developments in optical fibre technology have provided an excellent choice to civil engineers because of their small dimensions and good resolution and accuracy. Fibre optic sensors have attracted much attention for structural health monitoring (SHM), among which the Bragg grating (FBG) sensors are much more popular than others. Taking into account their miniaturised dimensions and relative robustness, FBGs appear as ideal sensors for integration between the fibres of FRP (fibre-reinforced polymer) rebars. These characteristics make this technology a valid candidate to be evaluated during the In2Track3 project as a reinforcement bar monitoring system.

Increased knowledge and implementable results

During the previous project In2Track2, an experimental campaign was carried out in the laboratory to evaluate the embedded-through section (ETS) shear strengthening technique, using carbon fibre reinforced polymers (CFRP) bars inserted through the cross-section of concrete beams. During this campaign, a monitoring system was also developed and tested with fibre-optic sensors embedded in the CFRP ETS bars to evaluate its capability to capture the axial strain distributions along the length of the ETS bar used as shear strengthening.

Photo: Alfredo García Farré and Carlos Hermosilla Carrasco

Figure 76-2 Vuoksenniskan underpass in Finland

In In2Track3, the technology developed in the previous phase was tested in a real demonstrator. For this purpose, a railway bridge of trough type was identified, and a shear strengthening of the bridge was carried out by introducing ETS bars with embedded fibre-optic sensors in the bars. The selected bridge was the Vuoksenniskan underpass, located on the Imatra-Parikkala Railway Line in Finland, see figure 76-2.

Six ETS bars were inserted at one end of the bridge, each of them equipped with 24 sensors distributed along the entire length of the bar, allowing the evaluation of axial stress distribution in the bar. The bars were monitored for four days, after which the data were analysed, confirming that the reinforcement bars were axially loaded when trains passed, as shown in figure 76-3. This demonstrated that the technology developed in the project is suitable for enhancing shear resistance in trough-type bridges. It was also established that fibre-optic sensors embedded in the CFRP ETS bars are a good alternative for structural health monitoring in real environments.

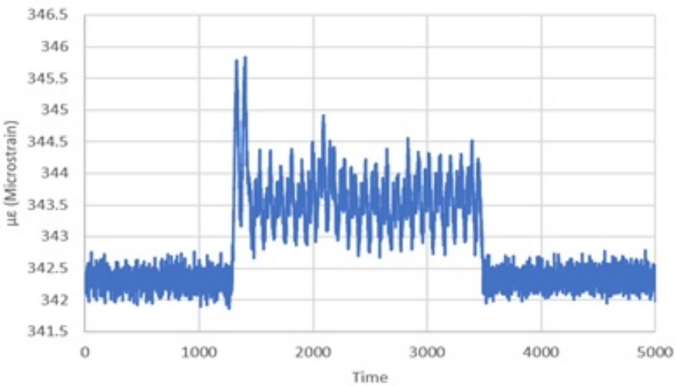


Figure 76-3 Strains during the passage of a train.

Implementation and open questions

The demonstrator served to validate the technology and address the initial pending questions. Acciona will continue investigating the development of ETS technology for the shear strengthening of concrete bridges with the aim of obtaining an effective reinforcement system that does not require traffic interruptions during reinforcement. In the In2Track3 project, the demonstration was carried out on a bridge with an un-cracked concrete section. For future research, it will be necessary to evaluate whether the technology is valid for reinforcing a bridge that is already cracked due to shear stresses.

Deliverable(s): D5.4


367

77 Demonstrator of ballast glueing on high-speed line

Aurelien Royet, Cédric Simon-Nguyen, Franck Arnoux, *SNCF Réseau*

Background

Ballasted track is widely used for high-speed lines on the SNCF Réseau network due to its excellent properties, such as good drainage of rainwater, transmission and distribution of trains loads, vibration damping, and easy track geometry rectification by maintenance operations such as tamping.

However, with the increase in operating speeds and traffic density, especially on high-speed lines, the ballasted track is increasingly stressed, leading to faster deterioration of the ballast bed which has an impact on the performance of the track and its geometry stability, requiring more maintenance efforts. Maintenance activities are very expensive, especially tamping and ballast renewal, which are required to maintain good track geometry quality. Track maintenance needs to increase dramatically with line exploitation speed, leading to a very high Total Cost of Ownership of ballasted high-speed lines.

Other problems related to ballasted track are stiffness or inertial variations in transition zones with switches and bridges, and also ballast flying that can occur on high-speed lines and may damage the rolling stock or the rail. As a result of a pressure wave effect due to the passage of a high-speed train, a grain of ballast can end up on the head of the rail and generate a ballast imprint or a dipped rail after being crushed by a wheel. The latter will evolve into a track geometry defect that can't be fixed by tamping but requires specific maintenance such as grinding, milling or rail replacement.

To address this problem, an innovative technical solution has been developed: ballast gluing. The innovation is in mechanical characteristics of the glue after drying. It fixes lightly the ballast grains in a given configuration to limit their movement and can eradicate the phenomenon of ballast flight. It widely increases track stability and track lifetime by reducing required maintenance efforts. The glue allows, if necessary, maintenance interventions like tamping.

Increased knowledge and implementable results

The ballast glue is an organo-mineral product in an aqueous phase that flows into the ballast, creating adhesive bridges between the grains. It gains its cohesive power through the evaporation of water. Depending on the quantity applied, the glued ballast depth can be more or less significant.

The ballast glue is environmentally friendly and allows to preserve the initial elasticity properties of the track as well as the capacity for drainage and tamping operations. A disadvantage is that the spreading of the glue is sensitive to weather conditions, particularly temperature and humidity, as well as to the clogging state of the ballast.

A test zone has been implemented on French East European High-Speed Line to evaluate the maintenance gain obtained after gluing the ballast. In July 2020, 2.7 km were glued on track 2 over a minimum of 10 cm depth along the entire track including the ballast shoulders. Track 1 was left unglued in order to compare both sites and study the gluing effect.

The track geometry evolution has been analysed by following the "NL" (standard deviation of the short-wavelength levelling defects, calculated over a length of 200m) which is a geometry quality indicator used in the French network to evaluate the deterioration of the track geometry: the higher the NL value, the more deteriorated the track geometry. The rail surface condition has also been analysed.

Regarding the track geometry aspect, no major improvement nor degradation has been noticed.

Regarding rail surface, tests showed the efficiency of ballast gluing to limit ballast flight. At this time however, rail defect limitation doesn't cost enough money to justify the standardization of ballast gluing: economic relevance must include a reduced maintenance of track geometry.

Implementation and open questions

Analysis must be conducted over a longer period to notice significant evolution on track maintenance cost: the experiment will be continued over several years. No maintenance operation was carried out in the glued area, allowing the ballast to be kept glued throughout the experiment. If tamping should be done, additional gluing operation should be considered.

It can be assumed that ballast gluing has no short-term benefit on track geometry when track doesn't present any specific maintenance problem. However, the surface condition of the rail can be improved.

More data needs to be accumulated, especially on areas of conventionally designed high-speed lines to conclude on the long-term benefit of ballast gluing. The test area mentioned above is indeed a new design with combined existing technologies that should reduce track maintenance (both on track 1 and 2): soft rail pads, gravel asphalt sub-layer, under sleeper pads.

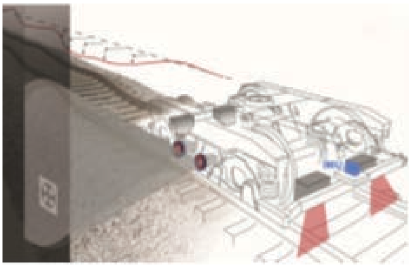
Deliverable(s): D3.1

78 Enhancement and demo of tamping parameters

Alejandro Salanova, Plasser & Theurer

Background

Improved measuring and recording technology could be used on every track maintenance machine to give precise information of the conditions on site to the infrastructure managers. This will optimise the maintenance and reduce the life cycle costs of the tracks. To head towards this goal, two technologies are evaluated, see figure78-1.



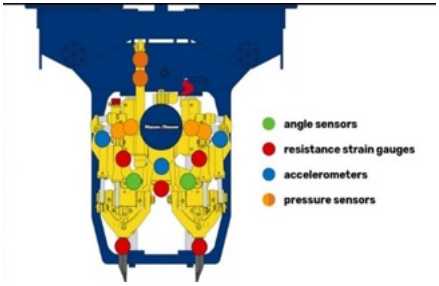


Figure 78-1 A representation of the ATG system: Marker, stereo cameras, IMU and laser sensors (left). The tamping unit (TAMP) with the sensors equipped (right)

The first Technology is a ballast reader tamping unit (TAMP), which enables the user to observe the movement of ballast throughout the entire tamping process. This makes it possible to time ballast cleaning or renewal. Additionally, the working parameters, as of tamping depth, time, number of insertions, are to be adapted to the respective ballast bed condition in the future, thus achieving a further increase in tamping quality, and reducing life-cycle costs. This is achieved with the implementation of accelerometers (blue), strain gauges (red), pressure sensors (yellow) and angle encoders (green) into a tamping unit and the frame of the machine itself. In In2Track3, the first step of this technology, the Ballast Condition Monitoring System (BCM), was tested which will lead us into a future automatically adaptable tamping machine.

The second technology is the so-called Absolute Track Measuring System (ATG). It consists of a georeferenced track geometry measurement system, which allows the user to locate the exact position of the machine even during high speeds, thanks to two stereo-cameras installed on the machine, and a special bolt installed on the rail posts.

Both technologies together with the information provided by the infrastructure manager synchronise providing information about the status of the ballast with very precise location.

Photo: Plasser&Theurer

Increased knowledge and implementable results

The two technologies were tested in Sweden. 1 km of single track was equipped with 16 markers on the poles next to the track as reference for the ATG.

The test sites feature different conditions:

- Kristianstad – Hässleholm (1-3): Stable, low degradation, medium/high standard deviation
- Osby – Hästveda (4-5): Stable situation, low degradation, low standard deviation
- Falkenberg area (6-8): Stable situation, low degradation, low standard deviation

One of the variables controlled has been the 'Penetration resistance force [kN]'. Figure 78-2 shows a comparison between fouled and clean ballast. In the fouled ballast the values of the penetration resistance force are higher due to its higher compaction.

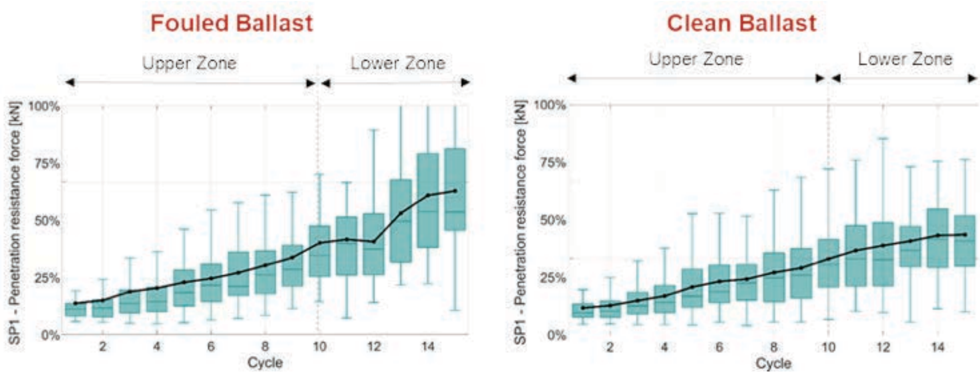


Figure 78-2 Penetration resistance force [kN] in fouled and clean ballast

ATG test run in Attarp

The ATG was tested in one section equipped with markers on 16 poles in a 1 km section. During the shift, 4 measurement runs were performed, recording using the stereo camera systems. At the same time, the ATG system delivered all the geometry-based information, consisting of trajectory data and track geometry data. This data was compared with the infrastructure data from Trafikverket, demonstrating its accuracy. Further data can be found in the annexes of the deliverable.

Implementation and open questions

To further develop the system data between locations should be compared. This provides an overview of the ballast situation around the world. Information on the status of the ballast is then used to device a precise tamping regime.

ATG is a final product available for integration on different machines and networks.

Deliverable(s): D3.3

79 Integration of heterogeneous data into a bridge asset management platform

Jose Solis-Hernandez, Paula Lopez-Arevalo, *Cemosa*

Background

During the course of the In2Track projects, different technologies have been developed in order to face the current challenges related to the aging of European infrastructure and the need to ensure the reliability and efficiency of the rail network. These challenges have been addressed by implementing new enhanced inspection and assessment methodologies, and proactive maintenance strategies.

In this context, a Remotely Operated Underwater Vehicle (ROUV) has been developed and demonstrated in different environments as a new inspection technology aiming to undertake operations that were conventionally expensive, dangerous, and challenging. Furthermore, from the data integration and analytics side, the CEMBOX Infra Platform, a Digital Twin oriented Bridge Asset Management Platform, has been conceived as a system to efficiently store, analyse and present diverse sources of information to evolve into a proactive maintenance approach. These technologies, presented in chapter 58 of this book, have been demonstrated in a series of use cases.

Increased knowledge and implementable results

The **ROUV technology** was demonstrated in various real-life scenarios, including:

- **Rules Dam, Granada (Spain)**. Initial visibility and stability tests.
- **Port of Marbella (Spain)**. State of submerged elements in different areas of the port.
- **Cable Tower, Marbella (Spain)**. State of submerged foundation of Marbella's cable tower.
- **Port of Málaga (Spain).** Overall inspection of the deck of the port.
- **Access bridges to Port of Málaga (Spain).** In depth inspection of scour and debris in the surroundings of the piles of these road and rail bridges.

These demonstrators allowed the retrieval of information in relation to the following items:

- The ROUV's behaviour in different scenarios and conditions, including high turbidity.
- The potential technical improvements to enhance inspections.
- The analysis of methodologies for robot maintenance.
- The development of a guideline for infrastructure underwater inspection.

The demonstration of the **CEMBOX Infra Platform** featured:

- A road bridge in Dúrcal, Granada (Spain).
- A railway bridge in Málaga (Spain).

These data-sets have been analysed using two different approaches.

The first approach is related to Operational Modal Analysis (OMA). Data coming from IoT sensors installed in the bridge in Dúrcal have been used to develop an algorithm for enhanced dynamic characterisation of bridges. The natural frequencies of the bridge have been identified, ten mode shapes have been characterised, and the damping has been calculated applying a semi-automatic approach and validation.

The second approach involves a full data-driven methodology, Machine Learning methodologies such as K-Nearest Neighbors, clustering techniques and Neural Networks were selected to execute anomaly detection workflows on the bridge, to motivate further inspection, assessment and maintenance activities.

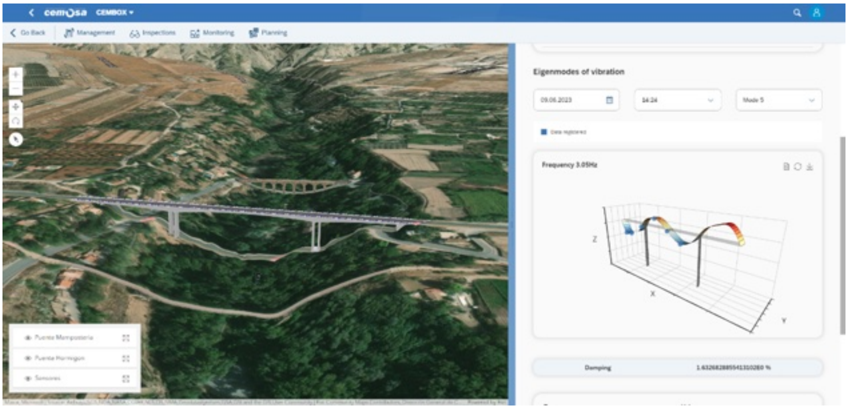


Figure 79-1 CEMBOX Infra demonstration in a concrete bridge in Dúrcal, Spain.

Implementation and open questions

As next steps for ROUV implementation, further demonstration case studies will be performed to incorporate the underwater inspection ROUV into a new service of CEMOSA. Specifically, the next crucial steps involve showcasing the capabilities of the ROUV in water bodies with varying degrees of turbidity and current strength. With respect to further integration of the system into the CEMBOX Platform, an additional specific interface will be created to integrate the retrieved videos, inspection information and data from water quality sensors and the rest of the ROUV sensors. This interface will be an added module inside the already existing inspection service.

So as to progress in the implementation and demonstration of the Structural Health Monitoring methodologies, a high-speed line (HSL) bridge and an earthwork with pathologies will serve as further demonstrators in the FP3-IAM4RAIL project. The HSL bridge will have an IoT monitoring system to retrieve data from the deck and the pot bearings. This case study will integrate enhanced Operational Modal Analysis (OMA) methodologies, ML, and degradation analysis on the deck and pot bearings. Simultaneously, the earthworks case study will entail slope monitoring, evaluating the condition state using satellite data, monitoring data, historical data, and geotechnics information. These developments will be included into the CEMBOX Infra Platform, creating the workflows for miscellaneous data integration, analysis, and the creation of specific interfaces for the BIM-GIS navigation and retrieval of information and analysis execution.

Deliverable(s): D5.4.

PUBLICATIONS

Deliverables Work Package 1

D1.1 Enhanced S&C system midterm report (Public)

- Data acquisition concepts integrated with sensor systems for CBM concepts and procedures
- S&C WSM Framework Structure, Concept - Use Case Calculation
- Sub-model concept: Crossing nose rail material behaviour - Use Case Calculation
- Laboratory-validated laser cladding and heat treatment processes
- VARS integration concept and validation plan
- Field Tests installation and preliminary optimisation (numerical model) on SNCF-R manganese cast frogs

D1.2 Scientific Methods and technical Concepts on Enhanced Switches & Crossings (Confidential)

- In-bearer sensor technology validated under controlled environment
- Sensor Networks technology validation under controlled environment
- Data acquisition concepts integrated with sensor systems for CBM concepts and procedures
- FEM Numerical Analysis of VARS Demonstrator
- Concept and Validation results on SNCF-R manganese cast frogs
- Analysis outcomes of the optimisation (numerical model) on NR manganese cast frogs

D1.3 Enhanced S&C system final report (Public)

- Data acquisition methods integrated with sensor systems for CBM concepts and procedures validation reports
- Data acquisition methods integrated with sensor systems for CBM concepts and procedures validation reports
- Data acquisition methods integrated with sensor systems for CBM concepts and procedures validation reports
- S&C WSM Framework Demonstration
- Validation results of the WSM Sub- model: Crossing nose rail material behaviour
- Laser cladding and heat treatment proceses roll-out in relevant environment
- VAE Demo validation report
- Analysis Outcomes of the optimisation (numerical model) on SNCF-R manganese cast frogs
- A brief high-level summary of what is included in D1.2

Deliverables Work Package 2

D2.1 Next generation S&C interim report (Confidential)

The Interim Report summarises progress of the activities by the different partners and the results achieved to date. It also highlights the outstanding activities and identify any risks or opportunities arising from the work done to date. It confirms the expected TRLs for each task.

D2.2 Next Generation S&C Modelling and simulations final report (Public)

The deliverable details the technological developments made within the two separate whole system modelling (WSM) approaches within WP2;

a) WSM incorporating multiple Next Generation components and sub-systems into a traditional S&C configuration
b) WSM of radically new S&C configuration designed from first principles

D2.3 Next Generation S&C Prototype Manufacture, Laboratory Testing and Model Calibration & Validation final report (Confidential)

The deliverable presents the prototype developments for Next Generation S&C kinematic systems, components and monitoring and sensing systems.

a) Next generation kinematic system prototype

b) Next generation S&C component prototypes

c) Next generation S&C monitoring and sensing prototypes

D2.4 Next Generation S&C Integration and Installation into Industry Relevant Environment (Confidential)

The deliverable presents the whole system design integration of the Next Generation S&C concept along with the final achievement in relation to the installation of a full-scale prototype demonstrator. Outputs from physical demonstrators are used to support WSM validation where possible.

a) Design integration and installation of next generation S&C demonstrator

b) Calibration and validation of whole-system models

D2.5 Radical New S&C Concept Design final report (Public)

The deliverable reports the progress made in developing radically new wheel-rail transfer concepts as a key enabler for the Next Generation S&C whole system design. The radical new tramway crossing is detailed and discussed within this deliverable.

a) Radical new wheel rail transfer

b) Radical new tramway crossing"

D2.6 Autonomous Inspection & Repair of Next Generation S&C (Public)

The deliverable presents the detailed design and results achieved from both the autonomous inspection and autonomous repair work streams.

a) Autonomous inspection of Next Generation S&C

b) Autonomous repair of Next Generation S&C

Deliverables Work Package 3

D3.1 Midterm report, Optimised track maintenance (Confidential)

The deliverable covers the background, approach and achieved results from Tasks T3.1-3.2 and corresponding sub-tasks in WP3, also what is left in order to perform expected results.

D3.2 Midterm report, Wheel/rail interaction, simulations and track monitoring (Confidential)

The deliverable covers the background, approach and achieved results from tasks T3.3-3.4 and corresponding sub-tasks in WP3, also what is left in order to perform expected results.

D3.3 Optimised Track Maintenance (Public)

The deliverable summarises all progress and final results for tasks T3.1-3.2 in WP3 concerning the track and track component requirements, maintenance. It reports what TRLs that have been reached, shows what was generated in T3.1 and 3.2, and the results from this work. It also shows how these results meet the KPIs which were defined for WP3.

D3.4 Wheel/rail interaction, simulations and track monitoring (Public)

The deliverable summarises all progress and final results for tasks T3.3-3.4 in WP3 concerning wheel/rail interaction, simulation and track monitoring. It reports what TRLs that have been reached. It shows what was generated in T3.3 and 3.4, and the results from related work. It also shows how these results meet the KPIs which were defined for WP3.

Deliverables Work Package 4

D4.1 Next Generation Track System Design Interim Report (Confidential)

The deliverable summarises progress of the activities by the different partners and the results achieved to report date within Task 4.1. It also highlights the outstanding activities and identifies any risks or opportunities arising from the work done to report date.

D4.2 Next Generation Track Inspection and Maintenance Interim Report (Confidential)

The deliverable summarises progress of the activities by the different partners and the results achieved to report date within Task 4.2. It also highlights the outstanding activities and identifies any risks or opportunities arising from the work done to report date.

D4.3 Next Generation Track System Design Final Report (Public)

D4.3 summarises progress on all activities undertaken during the project within Tasks 4.1 and 4.3, together with the final results. The report highlights any gaps or variances in results, if any, between what was achieved and what was expected. It will also recommend any further research work required to achieve a higher TRL.

D4.4 Next Generation Track Inspection and Maintenance Final Report (Public)

D4.4 summarises progress on all activities undertaken during the project within Task 4.2 and the final results. The report highlights any gaps or variances in results, if any, between what was achieved and what was expected. It also recommends further research work required to achieve a higher TRL.

Deliverables Work Package 5

D5.1 Scientific method descriptions for Tunnel and Bridge I2T3 Demonstrators (Confidential)

Report of ongoing and planned demonstrators for the remaining time of the project, including background, description of solution, approach and selected research methods for tasks T5.1-5.5 and corresponding sub-tasks in WP5. Some preliminary results are included. Report is divided into two parts; Tunnels and Bridges. Each demonstrator has a dedicated chapter and demonstrator leaders were editors for reporting of current status and schedule for remaining work.

D5.2 Performed Tunnel health monitoring I2T3 Demonstrators (Public)

Performed demonstrators and a final summary report compiling major results, technology potential, limitations, and considerations for implementation for task T5.1 and corresponding sub-tasks. Each demonstrator has a dedicated chapter and demonstrator leaders were editors for reporting of associated work, results discussion and analysis.

D5.3 Performed Tunnel improvement I2T3 Demonstrators (Public)

Performed demonstrators and a final summary report compiling major results, technology potential, limitations, and considerations for implementation for task T5.2 and corresponding sub-tasks. Each demonstrator has a dedicated chapter and demonstrator leaders were editors for reporting of associated work, results discussion and analysis. Summary of major findings and proposal for design strategy for tunnelling strengthening by using fibre reinforced concrete will be reported.

D5.4 Performed Bridge health monitoring I2T3 Demonstrators (Public)

Performed demonstrators and a final summary report compiling major results, technology potential, limitations, and considerations for implementation for task T5.3 and corresponding sub-tasks. Each demonstrator has a dedicated chapter and demonstrator leaders were editors for reporting of associated work, results discussion and analysis.

D5.5 Performed Bridge service capability improvement I2T3 Demonstrators (Public)

Performed demonstrators and a final summary report compiling major results, technology potential, limitations, and considerations for implementation for task T5.4 and corresponding sub-tasks. Each demonstrator has a dedicated chapter and demonstrator leaders were editors for reporting of associated work, results discussion and analysis. Report includes description of performed full-scale test on bridge.

Deliverables Work Package 6-8

WP6-8 are the administrative work packages, designed to follow-up and support work done in the technical work packages (1-5)

D6.1 Project Handbook (Public)

Description of procedures for document handling, naming convention of documents, rules for meetings, risk management procedures and management processes of possible amendments. This also includes production and management of all project templates for the participants and management meetings.

D6.2 Quality Assurance Report (Public)

Summary of all quality appraisal and verification sheets for proper evaluation of project quality.

D7.1 Report on quality assurance activities and follow-up on research progress (Public)

Report on quality assurance activities, Work progress chart, Overview of implemented/ implementable results

D8.1 Communication material about In2Track3 (Public)

Two project presentations; one intended for the general public with little detail knowledge about the railway system, and one intended for the project's interested parties with some knowledge about railway systems in Europe.

D8.2 Data management plan (Public)

The plan describes how the data produced in the project shall be managed during project life time and after the project ends.

D8.3 Dissemination and exploitation plan for the project (Public)

This report is a plan for how In2Track3 was supposed to perform activities to properly disseminate and exploit the project.

D8.4 Communication, dissemination and exploitation report

A concise description of how the plan D8.3 was executed within In2Track3 and results from those activities.

Scientific papers

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Dissertations and Licentiate theses

Dissertations

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Licentiate theses

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To address increasing railway transports on ageing infrastructure assets a European research program, Shift2Rail, was set up with six Innovation Programs. The project In2Track3 was the concluding project in a series of projects part of Innovation Program 3 "Cost-Efficient and Reliable High-Capacity Infrastructure". The project ran between January 2021 and December 2023.

The general Shift2Rail objectives were

- To enhance the existing capacity fulfilling user demand
- To increase the reliability delivering better and consistent quality of service
- To reduce the life cycle cost, increasing competitiveness of the European rail system and the European rail supply industry

In2Track3 addresses these objectives specifically for the track, switches and crossings (S&Cs), and bridge and tunnel assets.

The project, coordinated by Trafikverket, the Swedish Transport Administration, involved 25 project member companies and an additional 14 associated partners from 10 different countries participated in the project. The partners included infrastructure managers, technology developers, research institutes and universities, which provided a wide representation of the railway sector.

This concluding technical reports provides an overview that features 61 examples of research topics and 18 examples of research results demonstrated in operational use. More details can be found in the 22 technical deliverable reports of the project.

In2Track3

Shift2Rail

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TRAFIKVERKET