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RAIL4FUTURE

Resilient Digital Railway Systems to enhance performance

Annex to the 1st Interim Report
April, 2022

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1 Area 1 - Simulation Platform for Railway Systems

1.1 Current State: Concept and Applied Methodologies

The Rail4Future Virtual Validation and Simulation Platform will enable for the first time: A fully virtual assessment of the behavior of the railway infrastructure system by deploying large-scale simulations based on hybrid-models enhanced with AI capabilities, real-time data input from the railway operations and visual-analytics methods.

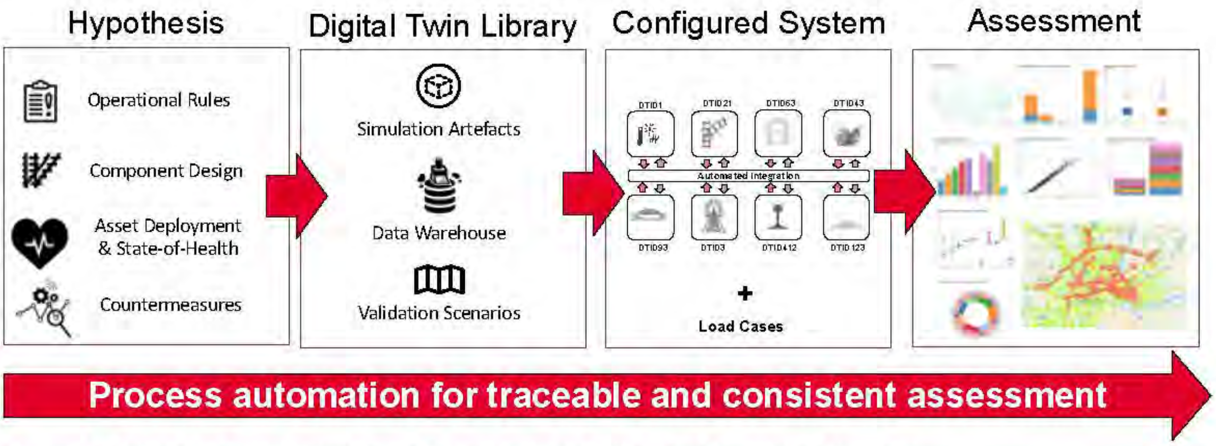


Figure 1: Rail4Future Simulation Platform for Railway Systems Concept

We propose a platform (Figure underneath) for the creation of a digital twin that aims to integrate measurement data, numerical models, and machine learning models from different railway subsystems into a holistic large-scale railway infrastructure platform.

The proposed R4F Platform framework can be summarized into six layers: asset layer, integration layer, infrastructure layer, function layer, visualization layer, and interaction layer. The Interaction Layer represents the user interaction with the Platform. For now, we identified four roles: User, which is the end user of the system, running the simulations; Asset Integrator, an expert within the company that runs an instance of the Platform and is responsible to integrate the assets (e.g. simulation and data) into the platform; Asset Provider, who creates assets from data and makes them available; Data Owner, which are the legal owner of Assets. The Asset Layer provides the blueprints for Assets that are able to be used in the platform. It defines three categories of assets (Numerical Models, Measurement Data, Machine Learning Models) and the requirements to be integrated (e.g. Meta Data).

All the data and models are integrated within the integration layer into the platform via their respective interfaces. The integration layer manages the import and integration of different data and models to the R4F Platform. The infrastructure layer is responsible for running simulations on the underlying hardware and controlling the simulation pipelines defined by the model and data integrators and providers. Together with the integration layer, it instantiates and executes simulations that are defined at the function layer. In the function layer, the simulation paths are either called up from previous simulations or, based on graphs, are newly compiled and processed in pipelines. In the end, the simulation results will be delivered to the visualization layer via defined interfaces. There these are processed and displayed according to the user's request.

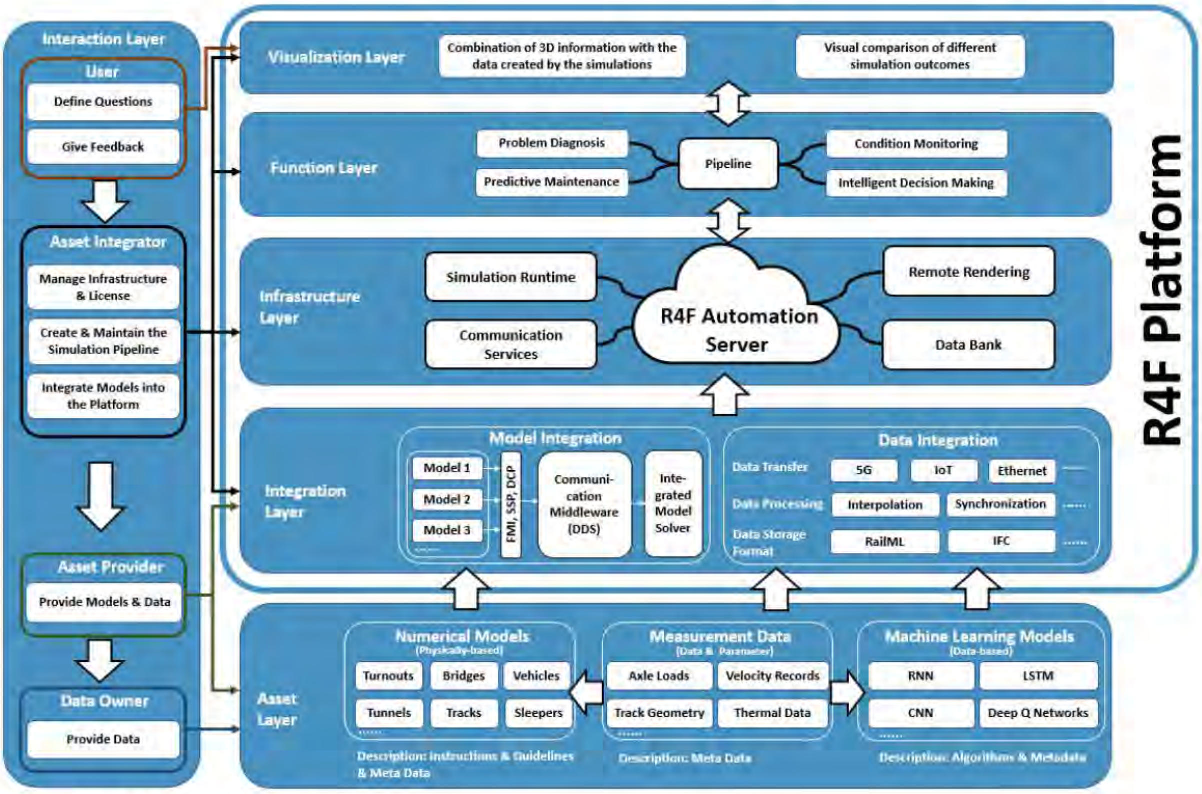


Figure 2: R4F Framework

Figure 3 shows a first implementation of the Platform approach. As use case a Vehicle-Track-Interaction model provided by Area 2 will showcase the workflow. Taking the viewpoint of the Asset Integrator after receiving the Model, first a Graph is generated that represents the dependencies of the submodels and data to each other, as well as the simulation workflow and the parameters that are needed. This is done with an application former developed by Virtual Vehicle that provides a Webinterface and a CLI for the graph generation. For every different simulation has to have is own graph, but in the future we plan to ease the execution by using Software like Enterprise Architect to generate SysML models that will be automatically transformed into the graph and validated. The Graph is then transformed into a Jenkins Pipeline which is responsible for the execution of the defined workflow. For now, the simulation results are written to a data storage and visualization tool (JFrog Artifactory) till we finished the interface specification towards the frontend provided by VRVis.

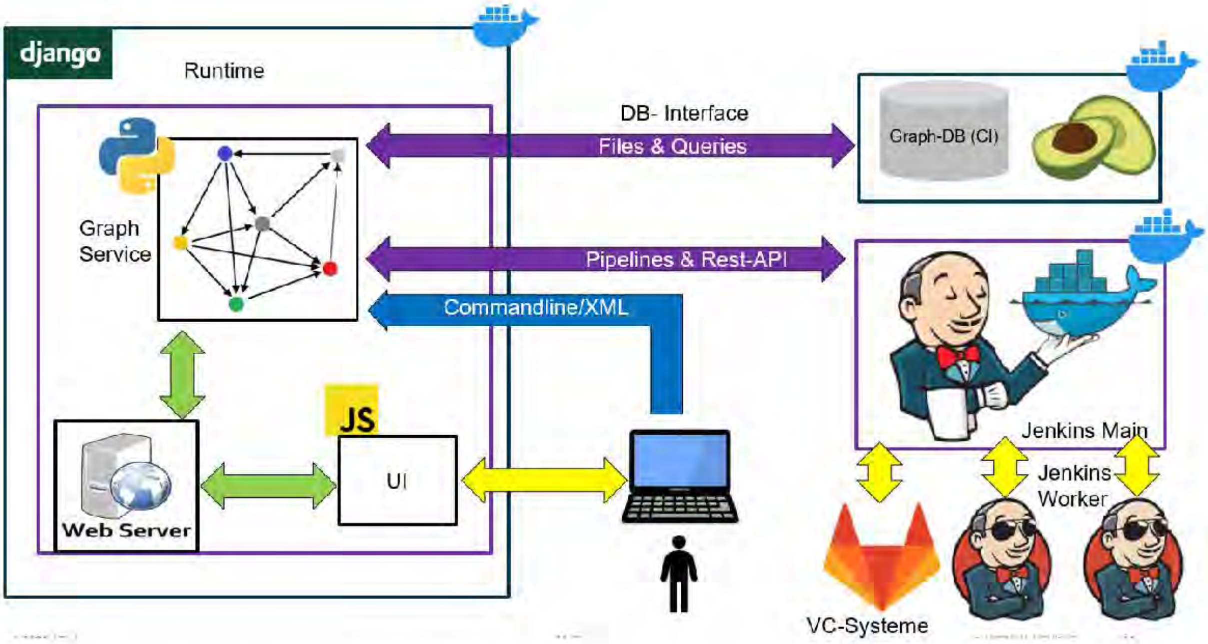


Figure 3: Integration approach

In short, the current state can be summarized as follows:

Integration Methodologies for a Holistic Railway System Simulations

- The R4F platform requirements and roles are successfully defined and listed.
- The Vehicle Track Interaction (VTI) model is successfully simulated as first demonstrator with MATLAB and their results with the measured data are shown in a graph for the first use case „Prediction of Track Geometry“.
- A concept for the R4F Platform was generated, which allows the implementation and optimization of separate parts of the platform as well as the definition of interfaces that will be needed between those parts (This work is also currently under review at the CIRP Design Conference 2022).

Visualization for Trust & Exploration

- A first visualization of point cloud technology of the railway system has been demonstrated before end of 2021.
- Integrating colours from photographs, and colouring parts of point clouds for visualization purposes is being tested. (see Figure 4)

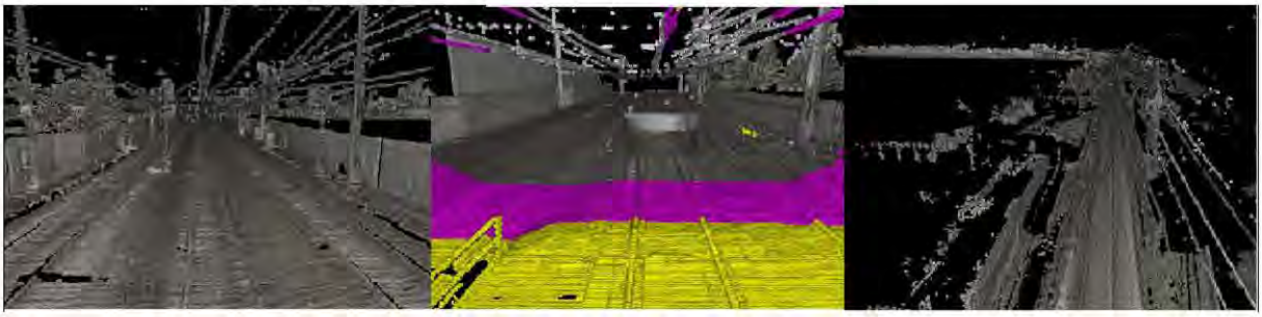

(a) (b) (c)

Figure 4: (a) Point cloud data; (b) Demonstrating projection into image space to retrieve colour information from images. The direction of the camera movement between successive images has to be calculated to determine which sections of the point cloud are behind or next to the camera (yellow and magenta); (c) A larger chunk of point cloud data.

1.2 References

[1] Zhang, Shiyao, et al. "A digital-twin-assisted fault diagnosis of railway point machine." 2021 IEEE 1st International Conference on Digital Twins and Parallel Intelligence (DTPI). IEEE, 2021.
(Link: https://ieeexplore.ieee.org/abstract/document/9540118?casa_token=4DdZnrQ4CTcAAAAA:ru_-w7UgvNNmXQvauLVoE2Ey0LSj9ffltiNptGo6v4zl7CTNRdBXUXPlpve1wUCkNWcBrV6u)

[2] Wang, Y., Steinbach, T., Klein, J., Anderl, R., 2021. Integration of model based system engineering into the digital twin concept. Procedia CIRP, Vol. 100, pp. 19–24.
(Link: https://www.sciencedirect.com/science/article/pii/S2212827121004613)

[3] Ahmadi, Miad, et al. "Adapting Digital Twin Technology in Electric Railway Power Systems." 2021 12th Power Electronics, Drive Systems, and Technologies Conference (PEDSTC). IEEE, 2021.
(Link: https://ieeexplore.ieee.org/abstract/document/9405876)

[4] Röhm, B., Emich, B., Anderl, R., 2021. Approach of simulation data management for the application of the digital simulation twin. Procedia CIRP, Vol. 100, pp. 421–426.
(Link: https://www.sciencedirect.com/science/article/pii/S2212827121005667)

[5] Rasheed, Adil, Omer San, and Trond Kvamsdal. "Digital twin: Values, challenges and enablers from a modeling perspective." Ieee Access 8 (2020): 21980-22012.
(Link: https://ieeexplore.ieee.org/abstract/document/8972429)

[6] Akbarian, Fatemeh, Emma Fitzgerald, and Maria Kihl. "Synchronization in digital twins for industrial control systems." arXiv preprint arXiv:2006.03447 (2020).
(Link: https://arxiv.org/abs/2006.03447)

[7] Kaewunruen, Sakdirat, and Qiang Lian. "Digital twin aided sustainability-based lifecycle management for railway turnout systems." Journal of Cleaner Production 228 (2019): 1537-1551.

(Link:https://www.sciencedirect.com/science/article/pii/S0959652619312351casa_token=B4JdjKJ4QUUAAAAA:1cUZoPplpILPvZBY49sl7svKHerG-V-ARk6Z8H-sG9moN4nCo94s9Zf3jsTO49iJ1XAavk6ieg)

[8] Tchana, Y., Ducellier, G., Remy, S., 2019. Designing a unique Digital Twin for linear infrastructures lifecycle management. Procedia CIRP, Vol. 84, pp. 545–549.
(Link: https://www.sciencedirect.com/science/article/pii/S221282711930798X)

[9] Wagner, R., Schleich, B., Haefner, B., Kuhnle, A., Wartzack, S., Lanza, G., 2019. Challenges and Potentials of Digital Twins and Industry 4.0 in Product Design and Production for High Performance Products. Procedia CIRP, Vol. 84, pp. 88–93.

[10] Vuckovic, Milena, and Johanna Schmidt. "Visual Analytics for Climate Change Detection in Meteorological Time-Series." Forecasting 3.2 (2021): 276-289.
(Link: https://www.mdpi.com/2571-9394/3/2/18)

[11] Cornel, Daniel, Andreas Buttinger, and Jürgen Waser. "Integrated Simulation and Visualization for Flood Management." Special Interest Group on Computer Graphics and Interactive Techniques Conference Talks. 2020.
(Link:https://dl.acm.org/doi/fullHtml/10.1145/3388767.3408335?casa_token=s9TdEZAQ89oAAAAA:eumtYOI5itVsM4ucrSP2iW1X5anUHUBDASIk9LwtOMtD-L4I7B_4be8gnCLN2b7EunjLpWE1QqjU)

[12] Gleicher, Michael. "Considerations for visualizing comparison." IEEE transactions on visualization and computer graphics 24.1 (2017): 413-423.
(Link:https://ieeexplore.ieee.org/abstract/document/8017615?casa_token=pQMybgRewOcAAAAA:wckGQAyTUI1svREtBLCL21pM17jy520aR8n2DiulSE0xAIdxJCGT7uAGCoy9SC1Z7DEblCs1)

[13] Ceneda, Davide, et al. "Characterizing guidance in visual analytics." IEEE transactions on visualization and computer graphics 23.1 (2016): 111-120.
(Link:https://ieeexplore.ieee.org/abstract/document/7534883?casa_token=0MpmNnwD6t0AAAAA:MGwtdlgkfm7KhSJacHluUt2ARHbyDPre5cY3FfBUyJepEs7iAeobgL9Ps8r5PQytW17txZBU)

[14] Kehrer, Johannes, and Helwig Hauser. "Visualization and visual analysis of multifaceted scientific data: A survey." IEEE transactions on visualization and computer graphics 19.3 (2012): 495-513.
(Link: https://ieeexplore.ieee.org/abstract/document/6185547?casa_token=i3ZUAY0k4okAAAAA:PVGD1hKFU5-6rJ229ny2K3b9B6PpGU49X6CKi3Z2C8ZOkXQYv37sz2MNeC2Rj8eJDTLm3jQB)

[15] Maschler, B., Braun, D., Jazdi, N., Weyrich, M., 2021. "Transfer learning as an enabler of the intelligent digital twin" Procedia CIRP, Vol. 100, pp. 127–132.
(Link: https://www.sciencedirect.com/science/article/pii/S2212827121004790)

[16] Ma, X., Cheng, J., Qi, Q., Tao, F., 2021. Artificial intelligence enhanced interaction in digital twin shop-floor. Procedia CIRP, Vol. 100, pp. 858–863.
(Link: https://www.sciencedirect.com/science/article/pii/S2212827121004935)

[17] Chen, Yuyang, et al. "Design and Verification of UAV Maneuver Decision Simulation System Based on Deep Q-learning Network." 2020 16th International Conference on Control, Automation, Robotics and Vision (ICARCV). IEEE, 2020.
(Link: https://ieeexplore.ieee.org/abstract/document/9305467)

[18] Tsunashima, Hitoshi. "Condition monitoring of railway tracks from car-body vibration using a machine learning technique." Applied Sciences 9.13 (2019)
(Link: https://www.mdpi.com/2076-3417/9/13/2734)

[19] Swischuk, Renee, et al. "Projection-based model reduction: Formulations for physics-based machine learning." Computers & Fluids 179 (2019): 704-717.
(Link:https://www.sciencedirect.com/science/article/pii/S0045793018304250?casa_token=ftTNe11_ZHcAAAAA:c_zEFYqqVlVfzQwY7P5uqw9rmmKGIBAQP3PoUoO4E0rOton8EW51G5pzTVMI56EHqU1Gmcqze)

[20] Bukhsh, Z. A., A. Saeed, and I. Stipanovic. "A machine learning approach for maintenance prediction of railway assets." Transp. Res. Arena 2018.
(Link: https://www.researchgate.net/profile/Zaharah-A-Bukhsh/publication/335491426_A_machine_learning_approach_for_maintenance_prediction_of_railway_assets/links/5d68fc5692851c154cc5ce54/A-machine-learning-approach-for-maintenance-prediction-of-railway-assets.pdf)

[21] Martin, Luke JW. "Predictive reasoning and machine learning for the enhancement of reliability in railway systems." International Conference on Reliability, Safety, and Security of Railway Systems. Springer, Cham, 2016.
(Link: https://link.springer.com/chapter/10.1007/978-3-319-33951-1_13)

[22] Yella, Siril, et. al. "Machine vision approach for automating vegetation detection on railway tracks." Journal of Intelligent Systems 22.2 (2013): 179-196.
(Link: https://www.degruyter.com/document/doi/10.1515/jisys-2013-0017/html)

2 Area 2: Reliable Railway Tracks

Area 2 research activities will enable Rail4Future vision by: Provide explanation & generate understanding of the railway system interactions and the underlying reasons of the specific behaviour of railway tracks and its impact on rail vehicles by means of basic research enhanced by novel digital twin methodologies combining different sources of data and advanced computational models.

Hybrid Simulation Model Development Accounting for Vehicle-Track Interaction

- Validated high-fidelity models of rail network elements (turnouts, rails (narrow and wide curves)) and vehicle subsystems each with different degrees of complexity, tailored to different requirements, handling different level of details and information
- Chains of methods combining physical high-fidelity models with measured data
- Context Information, data & model synchronization techniques
- Efficient test methods and system validation approaches: Design of Experiments, Development of Lab-Environment, Hybrid-Testing and Validation Techniques

Condition Monitoring for predictive maintenance with smart assets – Smart Turnout

- Methodologies for change detection of railway components (Rail and Turnout)
- Novel measurement concepts and technologies for non-incasive assessment of assets condition: Data fusion techniques, Continuous data generation concepts, Condition monitoring algorithms of sub-systems of a turnout (switch blades & turnout frogs), Trend Analysis and prognosis

Condition Monitoring for predictive maintenance with smart assets – Smart Rail

- Identification of a non-destructive, flexible test method for determining the longitudinal stresses in the rail profile, including validation in the laboratory and application on a demonstrator (test track)
- Methodology for splitting off the rail longitudinal residual stresses and determination of the safety-relevant rail longitudinal forces (safery against track distortion, rail breakage)
- Validation of the concept in the operation track (relevant environment)

2.1 Current State: Concept and Applied Methodologies

2.1.1 Hybrid Simulation Model Development Accounting for Vehicle–Track Interaction

Plasticity Model (Crossing Nose)

The semi-physical plasticity (SPP) model 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 the initial phase after installing a new crossing nose or after maintaining it. The development of the SPP model is based on a dataset generated with the full FEM based approach used in [1].

The operation of the SPP model – embedded into the framework shown in Figure 5 – starts with multi-body dynamics (MBD) simulations in Simpack environment with a full-scale vehicle model parametrized based on the Manchester Benchmark Vehicle [2], a commonly used Swedish turnout layout from the S&C simulation Benchmark [3] and a set of measured wheel profiles [4] (representing different wear conditions) to account for realistic track operating conditions.

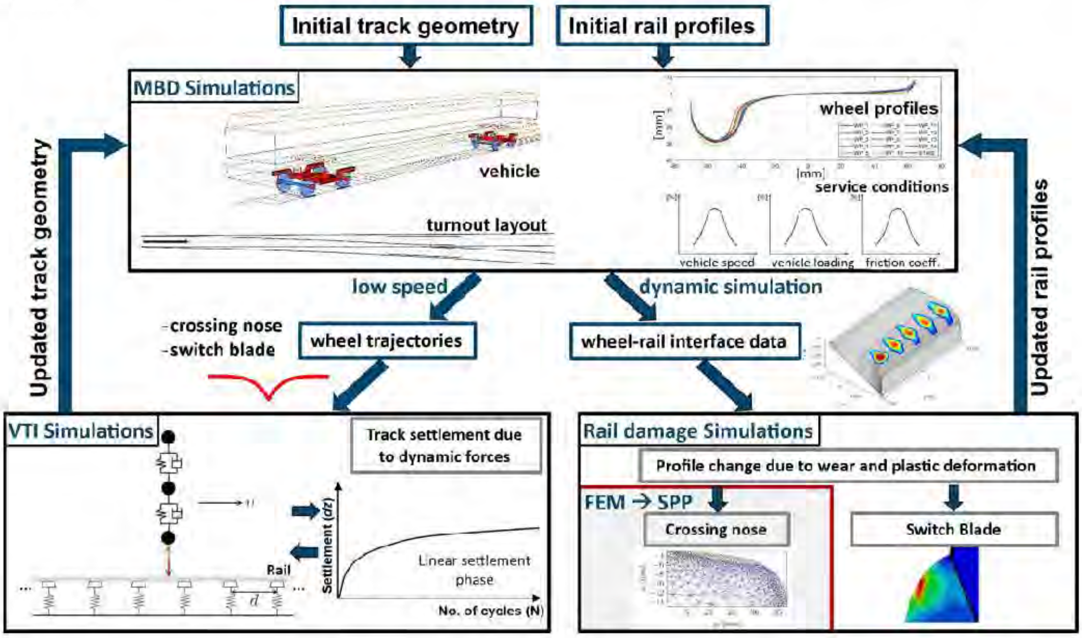
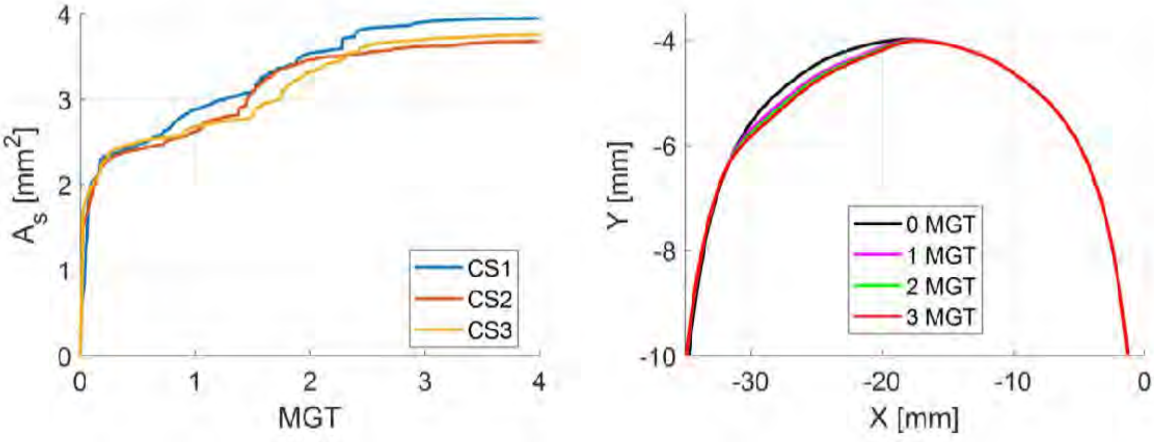


Figure 5: The Plasticity Model Overview as a part of the whole-system model-based framework

This parametrized MBD model is used to generate wheel-rail contact interface data (input to the lower right block in Figure 5) in the region of the crossing nose (such as maximum Hertzian contact pressure, contact patch dimensions, creepages, etc.). This wheel-rail contact data is then used as an input by the SPP model to perform two types of computations (two steps):

- Calculating the rail profile shape change area caused by plastic deformation (see Figure 6a and b). This calculation is based on analyses of the detailed FEM dataset generated for the rail material R350HT in combination with the MBD simulation results. This initial FEM dataset is required to calibrate the SPP model. In Figure 6a the development of the profile shape change area over traffic load (mega-gross tonnes: MGT) calculated from the FEM results is shown for three cross-sections. As expected, at the beginning a fast increase can be observed followed by a typical shake-down behaviour caused by material work hardening and reduction of contact stresses due to changed rail profile shapes.
- Rail profile shape calculations defining where on the rail profiles along the track the calculated shape change area values must be applied and how the shapes of the rail profiles look like after a certain traffic load increment (see Figure 6**b**). This is based

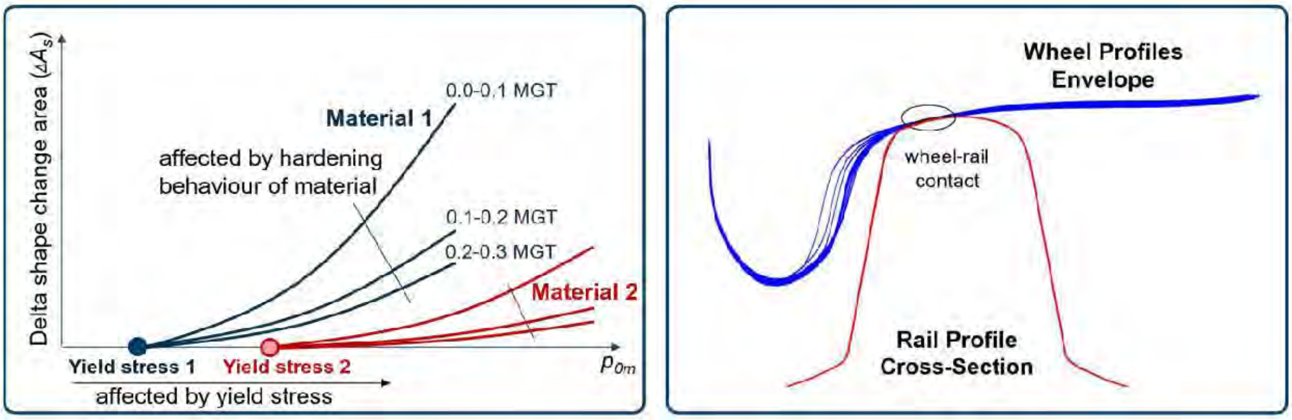
again on analyses of the detailed FEM dataset in combination with the MBD simulation results.



(a) *(b)*

Figure 6: Observations of the FEM-based rail profiles changes trend at the crossing panel

Plastic deformation in the crossing nose region is mainly driven by the extremely high contact normal stresses. Therefore, in a first approach, it is assumed that for a given traffic load increment (ΔMGT) a relationship between mean maximum contact pressure (p0m) and the increment of the shape change area (ΔAs) exists, see Figure 7. In this figure, the expected influence of the yield stress and the work hardening behaviour of the rail material is indicated.

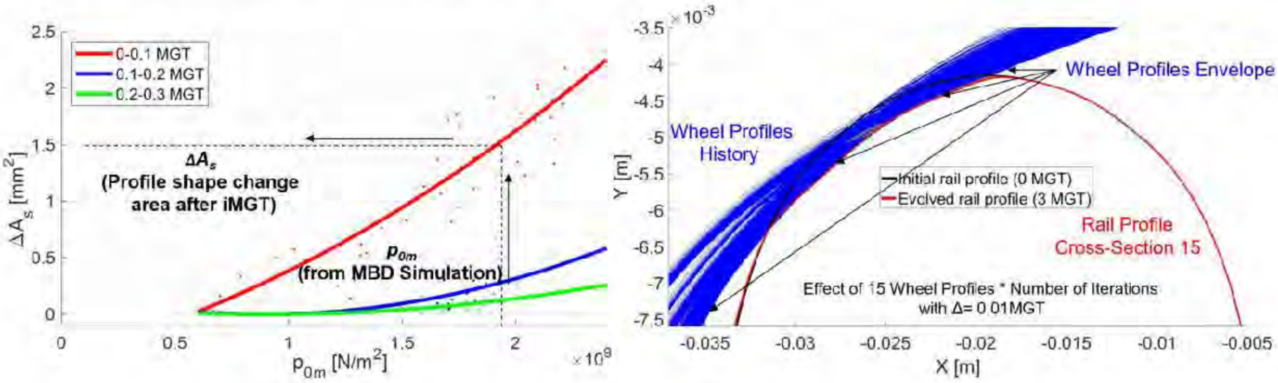


(a) *(b)*

Figure 7: Plasticity Model Fundamental Hypotheses for the profile form and material plasticity predictions

If this hypothesis is true, shape change area increments can be easily and fast calculated based on the MBD simulation results (see step 1 above). After calculating the shape change area increments along the track the rail profile shapes need to be accordingly modified (see step 2 above). Here, the main idea is that the rail profile shapes are determined by the wheel profiles collective at a given time (resulting profiles envelope taken from MBD simulations), see Figure 7b.

The proposed SPP model simulation results (Figure 8a and b) are shown to be in good correlation with plasticity calculations carried out with FEM based approach for R350HT steel grade and confirmed our initial hypotheses for both shape change area development and profile shape prediction based on the accumulated effect of the wheel profiles (Figure 8). Due to the semi-physical nature of the model, the computational time for such predictions was observed to be significantly improved as compared to the analogous FEM-based models. The publication based on the current model development results has been prepared and submitted to the Contact Mechanics Conference 2022 / Wear (Elsevier) Journal.



(a) *(b)*

Figure 8: Plasticity Model Validation of the proposed Hypotheses using the Hybrid MBD-PM based simulation results

FEM-Model for the WEL analysis

The analysis of the WELs starts with the preliminary studies based on the literature data and commonly used methods. Based on these investigations the following foundational 3 groups of considerations are reasoned and used for the model development:

- Common features of FE models: WEL found to be mostly linear elastic modelled [5,6,7,9]; 2D models commonly have plane strain elements (plane distortion state) [5,6,7,9]; WEL thickness ~ 0.2 mm [5,6,7,9,10]
- Possibilities of FEM:
  a) Elastoplastic material behavior
  b) Different materials
  c) Thermal (pre-)stresses
- Limitations of the FEM: Number of cycles (3 cycles [5] to max. 200 cycles f. 2D [9]), crack propagation is computationaly heavy due to re-meshing and fine meshes, crack initiation only indirectly possible via fatigue parameters

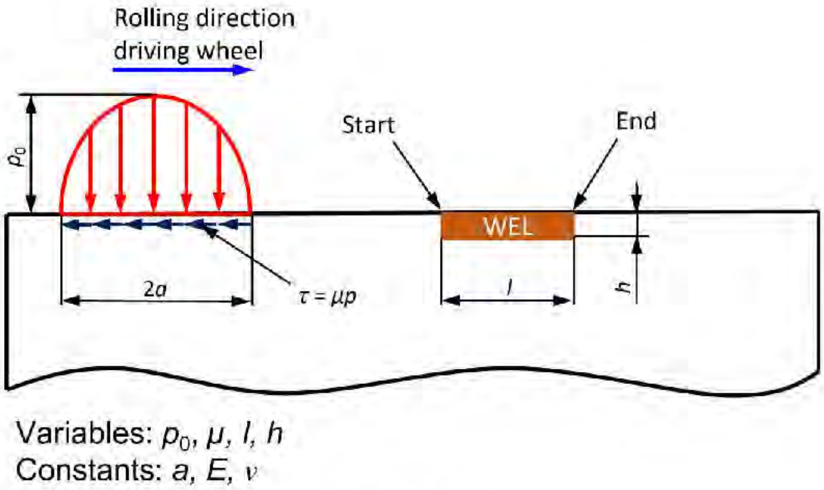


Figure 9: FEM-Model Scheme for the WELs analysis

Based on the literature analysis a 2D FEM-based model with the plain strain elements has been developed (Figure 9) for the parameter variation studies with the following main features:

- Full-scale contact (2a = 15 mm)
- Length and height of the model: 60 mm
- Element size 1 x 1 mm, at surface 1 x 0.1 mm
- Base material: elastic/elastoplastic
- WEL modelling (linear-elastic, thermally pre-stretched)

Rail Profile Prognosis Model

The model development methodology is based on the extended analysis of the field measurement data (Semmering, Sterbfritz) and build upon the consideration of the two foundational hypotheses:

- Rail Wear Form (wear curve) depends on the wheel collective presented in the traffic
  - Independent from the rail material (Figure 10)
  - Independent of the installation location (radius)

The wear calculation is performed based on calculation of the vertical wear (Δz) and wear area (Aw).

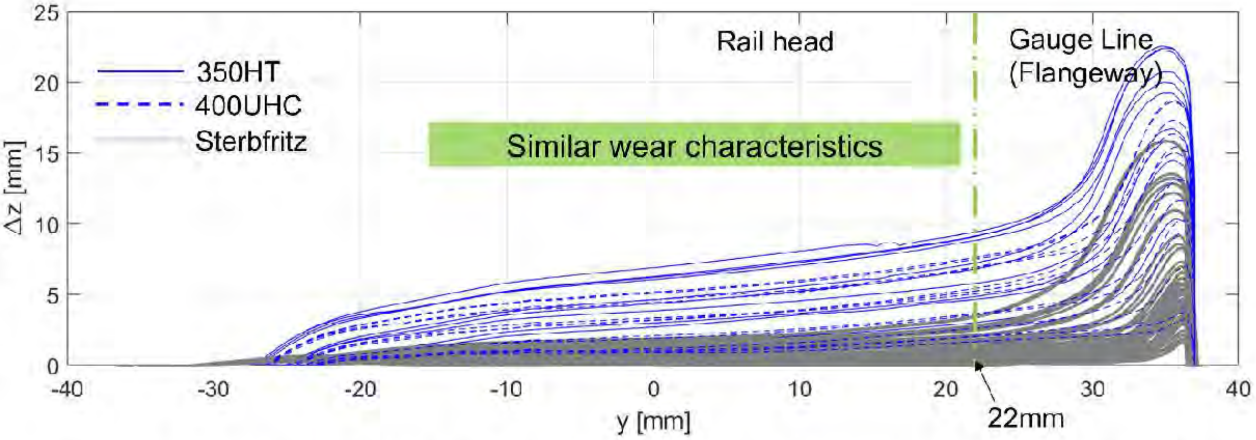


Figure 10: Rail Profile Prognosis Model. Analysis of the wear characteristics for the three different materials.

<u>Rail Profile Prognosis Model</u>

Based on the Comparative analysis of the MBD-Simulations based model results with the measurement data the following conclusion are made:

- Rail profile wear behavior has been analyzed based on Klamm-Schottwien (Semmering) field measurement data
- Comparison of wear development with Sterbfritz measurement data
- MBS simulations habe been performed to compare the loads (stresses) on the rail
- Good overall agreement of the ratios of the wear gradients has been achieved
- Outer rail: rail head τ_{max} (mild/severe wear), running edge T_γ (catastrophic wear)
- Inner rail: rail head T_γ (catastrophic wear), driving edge not comparable (no contact point during simulation - stationary curved travel)

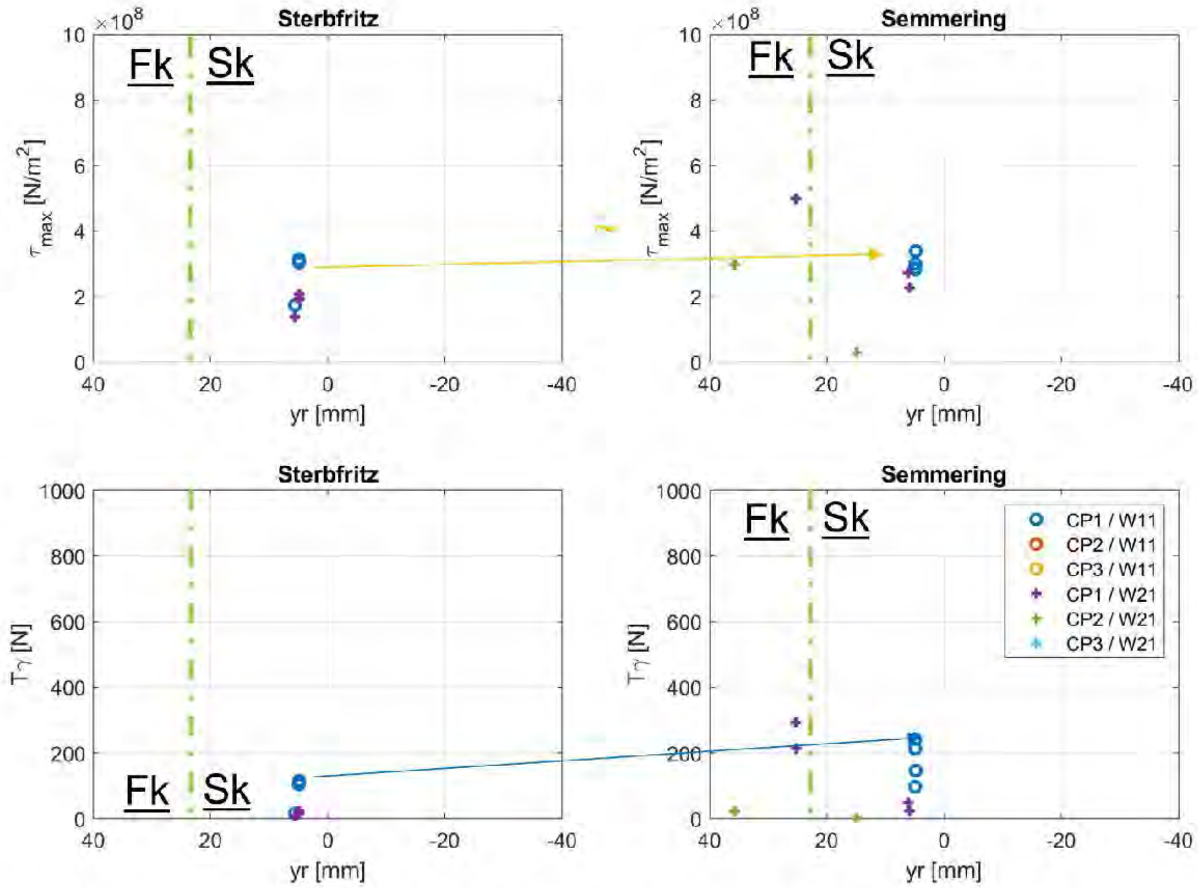


Figure 11: Comparison between the MBD-Simulation results. (Fk – Gauge Line (Flangeway), Sk – Rail Head). MBD Simulation exemplary results.

2.1.2 Condition Monitoring with smart assets – Smart Turnout

The first part of the project contains the definition of necessary data and methods. The three streams need partly different, but also overlapping and similar data.

Descriptive Approach New Measuring Devices: A hardware concept of the proposed railcar mounted multi-sensor platform.

A combination of non-invasive measurement methods for recording and monitoring rail infrastructure such as turnouts, rail joints, etc. The measured vibration and visual data of the rail tracks are combined with highly precise time and spatial (geo- reference) synchronisation data. This enables the recording and annotation of ground truth (training) data, needed for subsequent evaluation and monitoring.

The figure below shows the block diagram of the overall hardware concept of the measurement system including all sub components and its communication channels. The concept is developed by Joanneum Research in collaboration with the project partners Plasser & Theurer and HBK. The measurement system will be installed on a track recording car by the project partner Plasser & Theurer. HBK will provide the vibration sensors and the vibration signal recording hardware. The main sensors for data acquisition are a vibration sensor (1-3, 14) and a line-scan camera (4-8). For time and geo-synchronicity of the recorded data (9), we utilize the Precise Timing Protocol v2 (PTPv2) (10, 11, 15) and a high-end GNSS receiver (12, 13).

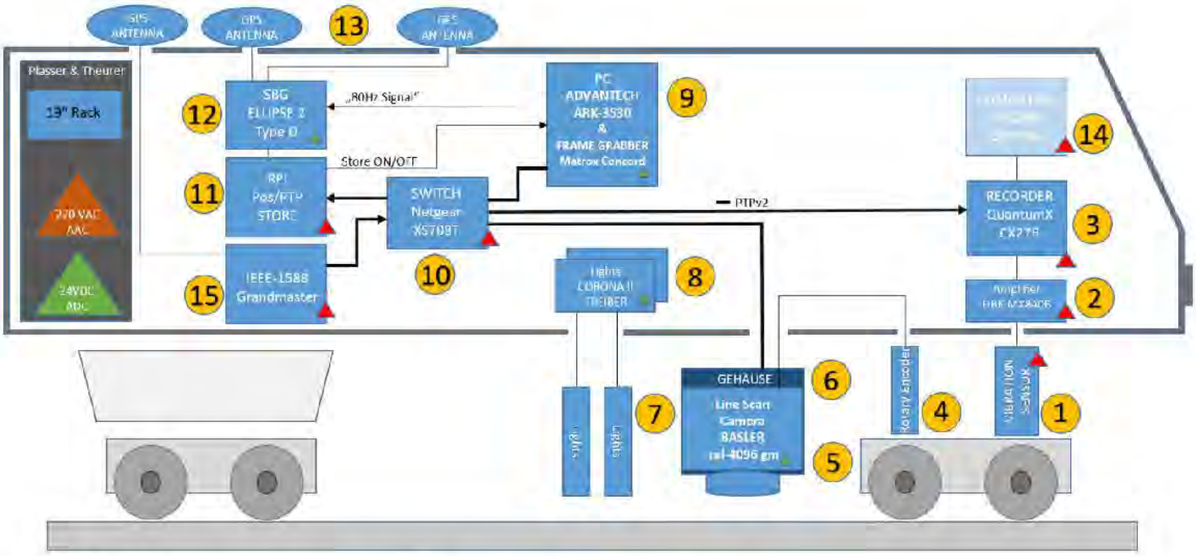


Figure 12: Hardware concept of the measurement system

Descriptive Approach Standard Measuring Car: The aim of this activities is to describe the condition and deterioration of individual turn- out components based on existing data. In contrast to open track, manual inspection is still the primary method for assessing the condition of turnouts. Although this enables safe railway operation due to the high level of competence of the employees, some disadvantages such as personnel in the danger zone, track closures, high costs and an unloaded measurement exist.

In addition, the data obtained from the inspection is not suitable for forecasts, which means that decisions in favour of the economic optimum can only be implemented with difficulty or not at all. Therefore, measurement data is needed to provide additional support for decision making leading to economic efficiency and safety, of course. The main data source for this project is ÖBB's measuring car, the EM250. More precisely, it is the output of the IMU system and various optical measuring systems. From this data source, robust prediction algorithms are to be implemented for use in a predictive maintenance concept. Additional data will be used for model verification and calibration.

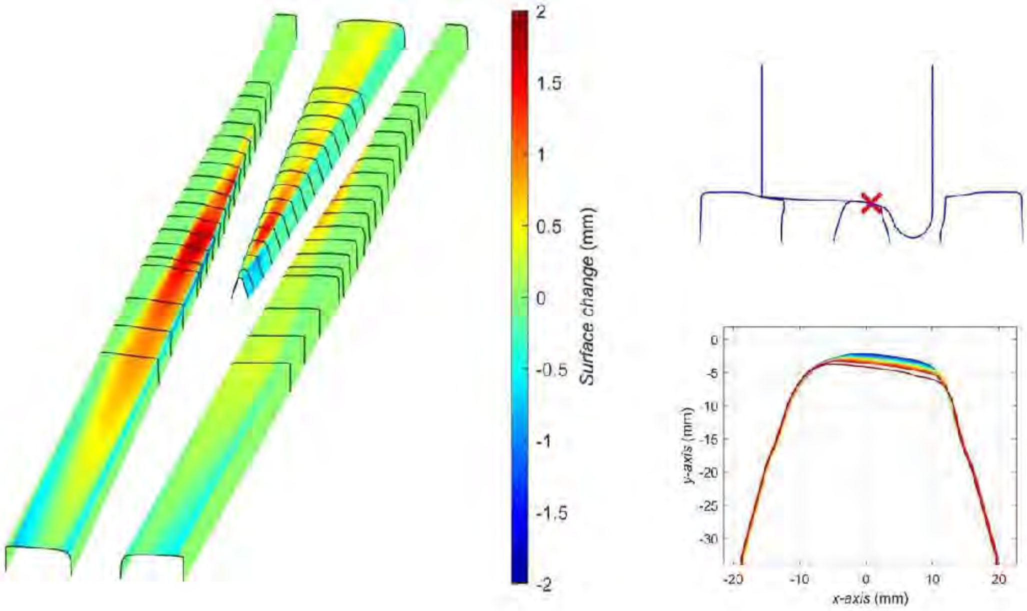


Figure 13: Calibri measurements [4]

The objective of the first project phase was to define a focus and the assets to be investigated. The focus lies on the quality behaviour of turnout components, especially the crossing nose. The rail surface signal, which is measured with a measuring system already mounted on the EM250, is the focus of the investigations. Since a turnout can only be meaningfully evaluated as a complete system, other data sources are also taken into account, some of which have already been investigated. Considering as many effects as possible, reliable prognosis algorithms are to be implemented for a predictive maintenance concept of turnouts.

Turnout	Criteria of consideration
T_R4F_03	Main turnout of project partner
T_R4F_08	Documented crossing nose exchange
T_R4F_12	Worn out insulated rail joint documented
T_R4F_21	Good documentation incl. crossing nose exchange
T_R4F_22	Good documentation incl. crossing nose exchange
T_R4F_24	Good documentation incl. crossing nose exchange
T_R4F_25	Good documentation incl. crossing nose exchange

For the turnouts listed underneath and installed in the ÖBB – Network, the following data have been provided or will be provided by the project partners.

- Asset classification and load spectrum
- Relevant measurement data of EM250
- List of executed maintenance actions (data base)

- Additional information about executed maintenance actions
- Technical drawings
- Calipri measurement for T_R4F_22

In addition, data on the asset classification, the load spectrum, data on maintenance measures carried out and measurement data from the EM250 are available for 29 of the 30 turnouts originally defined. For 19 of the 30 turnouts (ASC Leoben), additional information on maintenance measures already carried out is currently being collected.

Model-based assessment of S&C

Currently, inspection is carried out by means of fixed inspection cycles based on manual measurements or special inspection vehicles. In order to increase the efficiency of switch maintenance, more focus is placed on continuous monitoring of S&C. Information on the condition of the S&C can be collected by means of attached sensors on track or in-service vehicles with the aim of detecting faults at an early stage, analysing of root causes and making condition prognosis [6]. Therefore, methods and models are necessary to determine the operating state of the S&C on the basis of physical effects (model-based approaches) or on the basis of statistical behaviour (data-driven models) [7]. In many cases, the combination of both methodological approaches in the sense of hybrid modelling represents the best solution.

For the development of S&C condition monitoring algorithms, a broad dataset consisting of measured data (geometry and vehicle/track interaction) and simulation results is required. Multibody dynamic (MBD) simulation plays a particularly important role here. Through the reliable simulation of vehicle/track interaction, physical effects can be determined as a function of the condition and brought into model-based approaches as well as the parameter space of the existing measured datasets can be extended. Even with appropriately selected measuring intervals, measurements always represent a certain snapshot (measured variable plus environmental influences). In contrast, simulations have the great advantage that unknown parameters can be varied in a controlled manner. However, this requires validated models with a corresponding model depth as well as precise input data for the simulation scenarios.

Input sources for MBD simulation are profile geometry in rails and turnout zones, track irregularities and layout and operating conditions of the vehicle and track. There are different methods and procedures to capture this information. Data and information can be obtained from diagnosis vehicles, inspections, operational plans and external sources (e.g. weather). The questions arising in this context are, which steps are necessary for the preparation of data in order to be able to use them in MBD simulation and is it possible to simulate the development of the turnout condition with the current scope of data?

The concept of the work in this approach is shown in the following figure:

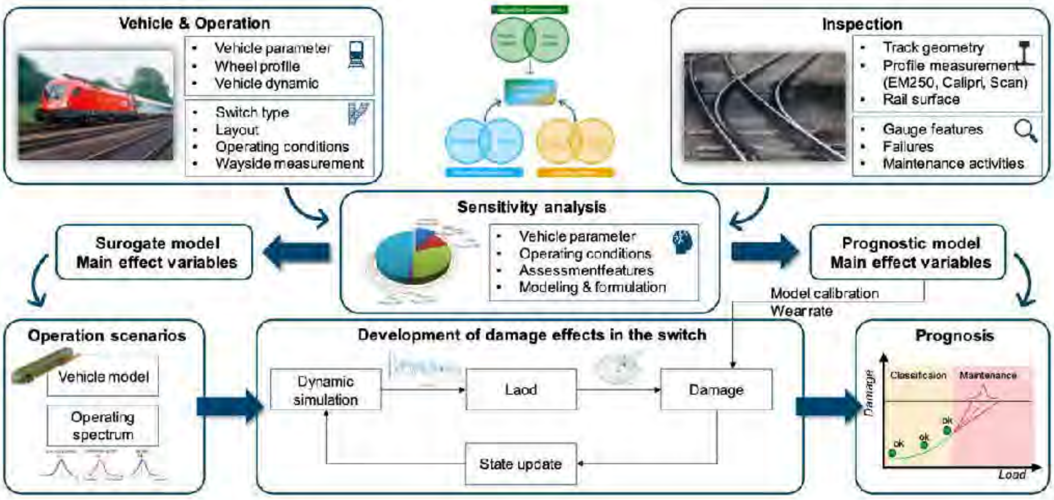


Figure 14: Concept for evaluation of S&C condition based on simulation

Based on the 'Trible Hybrid Approach' for solving problems of condition monitoring and condition prognosis of components in the railway system, different data sources are combined. Information on the vehicle and its operation is combined with data from maintenance (track geometry, rail profiles, rail surface, etc.). With this database, a sensitivity analysis is performed with the aim of testing the input parameters for their influence on the quality and robustness of the MBS simulation results. Furthermore, parameters are derived for the corresponding virtual modelling of the operation and for the prediction of the change of state of the S&C. Based on these results, scenarios for the operational simulation can subsequently be created and thus the development in the damage of the switch can be determined.

2.1.3 Condition Monitoring for predictive maintenance with smart assets – Smart Rail

Continuously welded rails (CWR), as found in the current rail network, have become the standard in recent decades (Wegner 2008a; Johnson 2004). Compared to rails with gaps, they are easier to maintain and can be used at higher speeds (Enshaeian and Rizzo 2021). In addition, CWRs lead to less wear on wheels and longer rail lifetimes (Zhang et al. 2018). Temperature changes lead to longitudinal stresses occurring in the rails, as they cannot expand or contract accordingly due to the welding (Wegner 2008a). In extreme cases, this can lead to rail breakage at low temperatures, while track warping can occur at excessively high temperatures. Both phenomena have led to the derailment of trains in the past. In order to reduce the loads on the rail at temperatures classified as critical, the speed of the trains is reduced, for example. However, this leads to economic losses and delays. In order to be able to better assess both the risk of a derailment and the necessity of arranging a speed restriction, it is essential to know the rail condition and to be able to assess and describe the stress state. The neutral temperature (NT) was introduced for this purpose.

Traditional methods of examining NT include cutting a rail and measuring the resulting rail contraction or the distance between the cut rail ends. Alternatively, strain gauges are used in this procedure. The NT can be calculated from the contraction of the rail and, if necessary, the rail can be welded again with an adjusted NT. However, this method is destructive, time-consuming and expensive. (Hurlebaus 2011; Wegner 2008a)

Basically, the methods can be divided into four categories:

1) Sound or vibration measurements
2) magnetic and eddy current based techniques
3) optical methods (e.g. X-ray or thermography)
4) strain measurement (DMS)

Table 1: Evaluation Matrix

Verfahren	Mobilität	Messdauer	Genauigkeit	Umwelteinflüsse	Empfindlichkeit bzgl. Oberflächengüte	Minimale Informationslänge (Längsrichtung)	Fehleranfälligkeit durch Fehlbedienung
Nicht-linearer Ultraschall	+	-	o	o	o	o	-
Raileigh-Wellen Spg-Messung	+	+	k.a.	o	o	o	-
Resonanzmessung (D'Stresen)	+	+	+	Zugspannung benötigt	o	o	-
Schienenvibration	o	-	k.a.	-	-	o	-
Bildgebende Verfahren	+	k.a.	k.a.	-	-	k.a.	k.a.
Magnetik und Barkhausen (MAPS)	o	-	-	+	+	o	o
Piezomagnetismus (StressProbe)		-/o	k.a.	o	o	o	o
Röntgendiffraktometer	+	-	o (variabel)	-	-	+	-
Dehnungsmessung	-	+	o	+	-	+	+

Sound and vibration measurements (especially ultrasonic testing and sound testing) offer great potential for determining the stress or neutral temperature on rails. The advantage of these methods is that they are well described in theory and are already used in other industrial sectors for stress determination on metallic components. In addition, a precise resolution can be achieved locally by means of ultrasound. The devices are portable. The disadvantages of these methods lie in their susceptibility to error by the operator, as the methods react sensitively to the coupling conditions of the different transducers, for example.

Magnetic and eddy current based techniques are already used in the determination of voltage and neutrality on rails (see MAPS). Advantages are the relatively precise (2-8°C depending on the source) measurement accuracy of the methods and the robustness against environmental influences as well as the portability of the devices. Disadvantages of the methods are that they require reference states as an adjustment and need a long measuring time.

The advantages of optical methods (e.g. X-ray or thermography) are that the devices are portable and can deliver precise measurement results with precise settings. The disadvantages of these methods are the high susceptibility to interference due to environmental influences and the increased susceptibility to interference by the user.

Strain gauges are used specifically at locations with increased risk for stress control. Advantages of the technology are precise accuracy and short measuring times as well as low susceptibility to interference by the user. Disadvantages of strain gages are the fixed application at a measuring point (no mobility) as well as a high sensitivity with regard to the surface quality.

2.2 References

[1] K. Six et al., “A whole system model framework to predict damage in turnouts,” Veh. Syst. Dyn., pp. 1–21, Oct. 2021. (Link: 10.1080/00423114.2021.1988116)

[2] Y. Bezin et al., “Multibody simulation benchmark for dynamic vehicle–track interaction in switches and crossings: results and method statements,” Veh. Syst. Dyn., 2021. (Link: doi: 10.1080/00423114.2021.1959038)

[3] Y. Bezin and B. A. Pålsson, “Multibody simulation benchmark for dynamic vehicle-track interaction in switches and crossings: modelling description and simulation tasks,” Veh. Syst. Dyn., 2021. (Link: doi: 10.1080/00423114.2021.1942079)

[4] B. A. Pålsson, “Optimisation of railway crossing geometry considering a representative set of wheel profiles,” Veh. Syst. Dyn., vol. 53, no. 2, pp. 274–301, Feb. 2015. (Link: doi: 10.1080/00423114.2014.998242)

[5] Zeng D. ; L. Lu ; Y. Gong ; Y. Zhang ; J. Zhang (2017) Influence of solid solution strengthening on spalling behavior of railway wheel steel, *Wear* **372-373**, S. 158-168

[6] Lian, Q. ; G. Deng ; A. Al-Juboori ; H. Li ; Z. Liu ; X. Wang ; H. Zhu (2019) Crack propagation behavior in white etching layer on rail steel surface, Engineering Failure Analysis **104**, S. 816-829)

[7] Lian, Q. ; G. Deng ; H. Zhu ; H. Li ; X. Wang ; Z. Liu (2020) Influence of white etching layer on rolling contact behavior at wheel-rail interface. Friction **8**, S. 1178–1196

[8] Sanusi, S. ; D. Fletcher (2017) The effect of white etching layer patches on a larger rail defect, In: MATEC Web of Conferences. 8th International Conference on Mechanical and Manufacturing Engineering 2017, 22-23 Juli 2017, Langkawi, Malaysia

[9] Meyer, K.A. ; R. Skrypnyk ; M. Pletz (2021) Efficient 3d finite element modeling of cyclic elasto-plastic rolling contact. Tribology International **161**

[10] Seo, J. ; S. Kwon ; H. Jun ; D. Lee (2011) Numerical stress analysis and rolling contact fatigue of White Etching Layer on rail steel. International Journal of Fatigue **33**, S. 203-211

[11] Fellinger, M.: Sustainable Asset Management for Turnouts - From measurement data analysis to behaviour and maintenance prediction, Dissertation at Graz University of Technology, 2020

[12] Plasser&Theurer, extracted on 24.11.2021, www.plassertheurer.com

[13] Hardware/Software Description, *Corrugation System COR-004*, 2004

[14] Voestalpine Railway Systems GmbH, *Calibri measurement data*, 2021

[15] ÖBB-Infrastruktur AG, *Technical drawing of a turnout*, 2021

[16] Weston P et al. Perspectives on railway track geometry condition monitoring from in-service railway vehicles. Vehicle System Dynamics. 2015;53(7):1063-1091. Available from: https://doi.org/10.1080/00423114.2015.1034730.

[17] Luber B et al. On-board wheel profile classification based on vehicle dynamics - from physical effects to machine learning. In: Lecture notes in mechanical engineering. Springer Interna- tional Publishing; 2020. p. 113{118.

[18] Bösl, Bernhard: Längsbewegung des Gleises als Folge von Normalkraftstörungen. In: Eisenbahntechnische Rundschau, Heft 41 (1992), S. 681–686.

[19] Braess, Hermann Patrick (2018): Sicherstellung einer langfristig guten Gleislage in atmenden Bögen. Dissertation. ETH Zürich, Zürich. Institut für Verkehrsplanung und Transportsysteme.

[20] Department of Structural Engineering (2010): Automated Measurement of Stress in Continuous Welded Rail.

[21] Di Lanza Scalea, Francesco; Nucera, Claudio; Phillips, Robert; Coccia, Stefano (2017): United States Patent US 9,689,760 B2. Anmeldenr: 14/356,615.

[22] Di Shu; Yin, Liang; Bu, Jin; Chen, Juan; Qi, Xin (2016): Application of a combined metal magnetic memory–magnetic Barkhausen noise technique for on-site detection of the stress- free temperature of a continuous welded rail. In: *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit* 230 (3), S. 774–783. DOI: 10.1177/0954409714562874.

[23] Djayaputra, Ferdinand (2010): DETERMINATION OF THE LONGITUDINAL STRESS IN RAILS. Texas A&M University.

[24] Dover, W. D.; Karé, R. F.; Brennan, F. P. (2005): StressProbe - A New Non-contacting Stress Measurement Technique. In: *Strain* 41 (4), S. 185–192. DOI: 10.1111/j.1475- 1305.2005.00229.x.

[25] Enshaeian, Alireza; Rizzo, Piervincenzo (2021): Stability of continuous welded rails: A state- of-the-art review of structural modeling and nondestructive evaluation. In: *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 095440972098666. DOI: 10.1177/0954409720986661.

[26] Fiford, Katherine (2019): VERSE Technical Information Pack. www.pandrol.com. Online verfügbar unter https://www.pandrol.com/de/product/verse-eisenbahn-stressmanagement/, zuletzt geprüft am 25.05.2021.

[27] Hurlebaus, Stefan (2011): Determination of Longitudinal Stress in Rails. Final Report for Safety IDEA Project 15. Texas Transportation Institute.

[28] Hurlebaus, Stefan; Jacobs, Laurence J. (2006): Dual-probe laser interferometer for structural health monitoring. In: *The Journal of the Acoustical Society of America* 119 (4), S. 1923–1925. DOI: 10.1121/1.2170442.

[29] Hurley, Samuel James (2014): DEVELOPMENT OF A LONGITUDINAL RAIL STRESS MEASUREMENT DEVICE. Master thesis. Texas A&M University, Texas.

[30] Johnson, Erland (2004): Measurement of forces and neutral temperatures in railway rails - an introductory study. Swedish National Testing and Research Institute.

[31] Kish, Andrew; McWilliams, Ryan, S.; Harrison, Harols: Track Buckling Hazard Detection and Rail Stress Management.

[32] Knopf, Katelyn; Rizos, Dimitris C.; Qian, Yu; Sutton, Michael (2021): A non-contacting system for rail neutral temperature and stress measurements: Concept development. In: *Structural Health Monitoring* 20 (1), S. 84–100. DOI: 10.1177/1475921720923116.

[33] Liu, Ganzhong; Liu, Hao; Wei, Anqi; Xiao, Jieling; Wang, Ping; Li, Shaozheng (2018): A new device for stress monitoring in continuously welded rails using bi-directional strain method. In: *J. Mod. Transport.* 26 (3), S. 179–188. DOI: 10.1007/s40534-018-0164-z.

[34] Nucera, Claudio; Di Lanza Scalea, Francesco (2014): Nondestructive measurement of neutral temperature in continuous welded rails by nonlinear ultrasonic guided waves. In: *The Journal of the Acoustical Society of America* 136 (5), S. 2561–2574. DOI: 10.1121/1.4896463.

[35] Oberst, Sebastian; Halkon, Benjamin; Ji, Jinchen; Brown, Terry (2021): Vibration Engineering for a Sustainable Future. Cham: Springer International Publishing.

[36] Senta Pessel (2020): Beitrag zur wirklichkeitsnahen Beschreibung von Rissen in Eisenbahnschienenfüßen. Dissertation. Technische Universität München, München. Lehrstuhl für Metallbau.

[37] Weaver, Richard (2006): Vibration Measurement of Rail Stress. University of Illinois. Innovations Deserving Exploratory Analysis Programs.

[38] Wegner, Alfred (2008): Zerstörungsfreie Railscan-Neutraltemperaturprüfung. In: *EI- Eisenbahningen*, S. 38–42. Online verfügbar unter https://www.elektro-thermit.de/fileadmin/et/user_upload/PDF/Publikationen/38_43_Wegner.pdf.

[39] Wegner, Alfred (2011): Zerstörungsfreie Verspanngrad- und Neutraltemperaturprüfung. In: *ETR* (9), S. 66–67. Online verfügbar unter https://www.elektro-thermit.de/fileadmin/et/user_upload/PDF/Publikationen/66_67_Wegner_Report.pdf.

[40] Wegner, Alfred; Kilian, Peter; Cramer, Hans-Otto (2008): Zerstörungsfreie Überwachung der Schienenlängsspannungen im Rahmen des Projekts City Tunnel Leipzig. 7. Chemnitzer Bahnkreis, Chemnitz. Online verfügbar unter http://arxiv.org/pdf/1109.3392v1.

[41] Zerstörungsfreie Werkstück- und Werkstoffprüfung. Die gebräuchlichsten Verfahren im Überblick (2019). 5., aktualisierte Auflage. Renningen: expert (Kontakt et Studium, Band 243).

[42] Zhang, Merrina; Roghani, Alireza; Barker, Christian (2018): Track research: longitudinal rail stress management gap analysis research report (phase 1).

[43] Zhang, Ralph; Wu, Helen (2013): Stability Analysis of Turnouts in Continuous Welded Rail Track.

3 Area 3: Reliable bridges and tunnels

According to current guidelines in Austria, railway structures, in particular so bridges and tunnels, need to be designed for a lifetime of (at least) 120 years and 150 years, respectively. This rather large time span renders railway systems as both ecologically and economically competitive players in the transportation world. However, predicting structural behavior for such an extended future time span poses severe, and still largely open, scientific and technological challenges. In the case of steel bridges, the latter are associated with *material fatigue*, i.e., crack development and growth under millions of load alternations, while in the case of concrete tunnels subjected to sustained ground action, the open challenge is the quantification of decaying, but generally *uncessable creep* deformations. The latter stem from the action of water at the atomistic scale, and their impact gains increasing attention in the scientific community [1], [2].

Reliable Railway Bridges

- Validated fatigue load model based on historic and current traffic loads
  Refined methods for reliability assessment and (probabilistic) prediction modelling of bridges prone to fatigue failure
- "3E Structural Health Monitoring (Effective, Economic and Easy-to-use) and sensor systems for crack detection based on advanced fracture mechanical models

Reliable Railway Tunnels

- Description of the physical behavior of tunnel structures subjected to ground pressure
- Deep insights of mechanism occurring in comprehensive constitutive engineering structures
- New methods for structural analysis of highly complex structural compositions
- Validated hybrid models with data from existing tunnel structures
- Level of loading of segmented and lined tunnels

3.1 Current State: Concept and Applied Methodologies

3.1.1 Reliable Bridges

The idea is to develop route-specific fatigue load models based on historic traffic loads and recent traffic load data provided by network checkpoints of the ÖBB (the Austrian Federal Railways), and combine these models with innovative monitoring and sensor systems for crack detection and propagation (such as acoustic emission and distributed fibre optical sensor systems) as well as advanced fracture mechanics approaches [3]. This will allow for estimating the remaining service life of steel bridges [4], and lay the ground for foresighted maintenance activities. On the level of numerical realization, the aforementioned combination of models and data will be fed into a finite-element-based digital twin of the bridge [5], also comprising

[illegible] yellow (midplants only)

probabilistic methods [6], so as to avoid an overly conservative estimate for the remaining service life.

Experimental research, analysis and validation will be integrated into a platform called Bridge LAB. It concerns dynamic fatigue tests considering dynamic properties, dynamic amplification factors and load distributions, to be performed at three levels: (i) in the laboratory, (ii) on-site in a 'secure environment' with controlled boundary conditions, and (iii) on bridge structures in service. This will allow '3E' Structural Health Monitoring, characterized as Effective, Economic and Easy-to-use. Figure 15provides an overview of the research activities described.

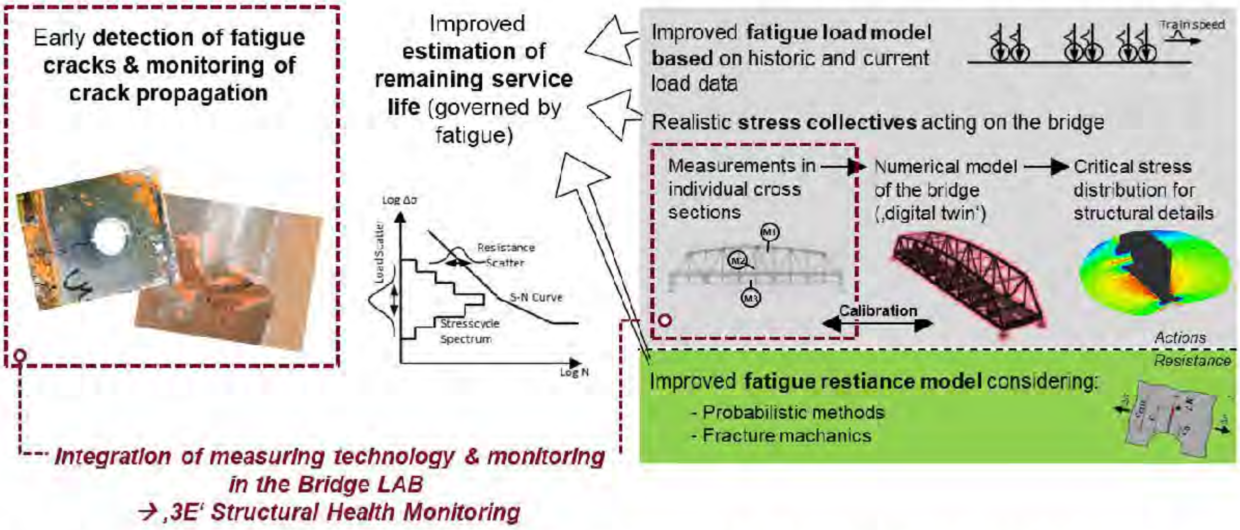


Figure 15: Overview of research activities for assessment of steel bridges prone to fatigue failure

Data collection and generation for bridges

Structural data

- geometry of bridge structures and individual members (from drawings and on-site measurements)

Monitoring data

- train load data (axle loads, distances, speed, measured on track)
- global structural response of the bridge (strains in main girders, inclinations, displacements, ...)
- global dynamic response of the bridge (accelerations, mode shapes, damping)
- local structural response at fatigue critical details (strains, strain distributions, acoustic emissions)
- temperature values (measured on-site)

Material data of extracted bridge members

- tensile strength
- elasticity
- fracture toughness parameters

Bridge sites

- Steel bridges in operation (bridge Eschenau, Salzburg; Walzenbauernbridge, Styria)
- One urban historic bridge structure in Vienna (Otto Wagner bridge)
- One structure out of service, transferred to the ÖBB's bridge testing facility

3.1.2 Reliable Tunnels

The idea is to combine the latest state-of-the-art in material physics and mechanics, to which the project partners of Rail4Future have been continuously contributing, with the wealth of monitoring data available on Austrian tunnel construction sites, and dedicated laboratory tests concerning chemical kinetics and creep, performed at the Institute for Mechanics of Materials and Structures at TU Wien (Vienna University of Technology). This combination will be essentially driven by the theoretical tools of analytical mechanics, allowing for the formulation of *rules* in terms of closed mathematical formulae provided in the framework of state-of-the-art computer algebra systems dedicated to the symbolic treatment of (differential) equations. In this way, both efficient and reliable components are to be gained to play a central role in the integrative artificial intelligence and machine learning ecosystem planned within Rail4Future.

From a material mechanics perspective, the prognosis challenge is tackled by means of upscaling, in space *and* time, of creep properties of calcium-silicate hydrates from the realm of minutes and micrometers to that of years and tens of meters. Recent progress on the broad global scale of engineering science, in both experimental and computational multiscale mechanics, concerning indentation probing [7], homogenization theory [8], and ultra-short creep testing [9], renders this challenge as a feasible task. From a structural mechanics perspective, Rail4Future has access to very innovative tunnel monitoring systems (including detailed geodetic measurements, fiber-optics, vibrating wire sensors), which, in combination with latest theoretical developments in (chemically) aging viscoelastic shell theory, hold the promise to allow for re-construction of the ground action and its effect of the utilization of the lining shell, not only in "real time", but also for the future. In this way, the theoretical understanding of recent large-scale testing activities [10], is being transferred to NATM as well as mechanized tunnel driving activities. As a result, a suite of hybrid analyses performed on a given tunnel structure will allow for the long-term prognosis of the behavior of the latter, providing important intervention indicators such heavily loaded regions to be expected at some time point in the future, see Figure 2.

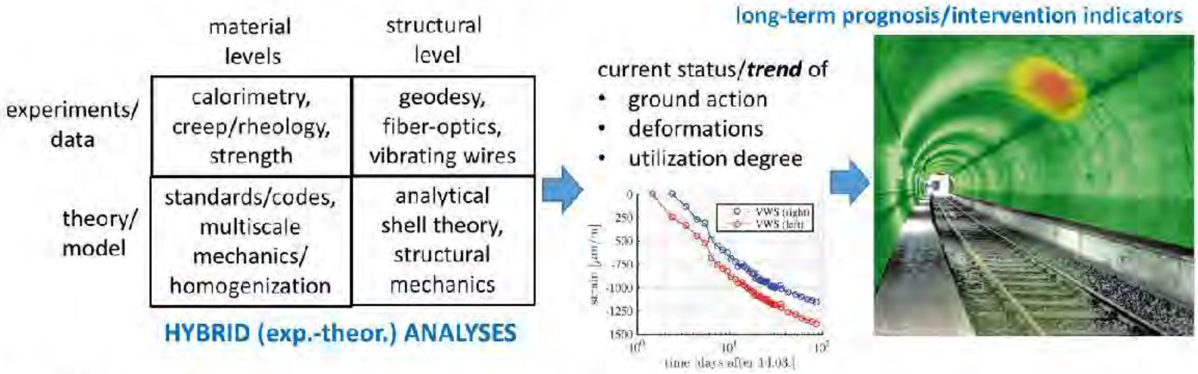


Figure 16: Hybrid analyses for long-term prognosis of tunnel behavior

Data collection and generation for tunnels

Structural data

- geometry of the cross-sections
- geometry of the segments

Monitoring data

- displacement values (geodetic laser-optical displacement measurements)
- strain values (strain gauge attached to rebar, fiber optic sensor cables fixed on the reinforcement)
- temperature values (temperature sensor inside shell)

Material data

- shotcrete/concrete (cement, aggregates, admixtures, additions, w/c ratio, strength, Young's modulus, creep characteristics, kinetics from calorimetry)
- reinforcement
- backfill of tunnel linings
- geological conditions

Tunnel construction types and sites

- NATM tunnel linings
- segmental tunnel linings
- Koralmtunnel (KAT)
- Granitztaltunnel
- Semmering Basis Tunnel (SBT)
- Sieberg Tunnel (historical data/benchmark)

3.2 References

[1] ZB Bażant, Zdenek P and Hubler, Mija H and Yu, Qiang, "Excessive creep deflections: An awakening," *Concrete international,* vol. 8, pp. 44-46, 2011.

[2] Hellmich, Christian and Pichler, Bernhard and Heissenberger, Roman and Moritz, Bernd, "150 years reliable railway tunnels--Extending the hybrid method for the long-term safety assessment," *Geomechanics and Tunnelling,* vol. 13, pp. 538-546, 2020.

[3] Institut für Stahlbau, "RLD-Genietete Stahlbrücken, Bestimmung der Restlebensdauer mit Bruchmechanikprognosen, Projektgesantbereich, ÖBB-Inferastruktur AG," TU Graz, Graz, 2019.

[4] Kühn, Bertram, "Assessment of existing steel structures-recommendations for estimation of the remaining fatigue life," *Procedia Engineering,* vol. 66, pp. 3-11, 2013.

[5] Zárate, Boris A and Caicedo, Juan M, "Finite element model updating: Multiple alternatives," *Engineering Structures,* vol. 30, pp. 3724-3730, 2008.

[6] Lachinger, S and Aichinger, C and Tamparopoulos, A and Strauss, A, "Discussion on the probabilistic assessment of fatigue with respect to reference periods," *Life-Cycle of Engineering Systems,* pp. 1125-1129, 2016.

[7] Baronet, J and Sorelli, L and Charron, J-P and Vandamme, M and Sanahuja, J, "A two-scale method to rapidly characterize the logarithmic basic creep of concrete by coupling microindentation and uniaxial compression creep test," *Cement and Concrete Composites,* vol. 125, p. 104274, 2022.

[8] Königsberger, Markus and Pichler, Bernhard and Hellmich, Christian, "Multiscale poro-elasticity of densifying calcium-silicate hydrates in cement paste: an experimentally validated continuum micromechanics approach," *International Journal of Engineering Science,* vol. 147, p. 103196, 2020.

[9] Irfan-ul-Hassan, M and Pichler, B and Reihsner, R and Hellmich, Ch, "Elastic and creep properties of young cement paste, as determined from hourly repeated minute-long quasi-static tests," *Cement and Concrete Research,* vol. 82, pp. 36-49, 2016.

[10] Zhang, Jiao-Long and Vida, Christoffer and Yuan, Yong and Hellmich, Christian and Mang, Herbert A and Pichler, Bernhard, "A hybrid analysis method for displacement-monitored segmented circular tunnel rings," *Engineering Structures,* vol. 148, pp. 839-856, 2017.