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Smart Autonomous Diagnostics of Switches and Crossings

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Abstract

This paper shows the results of the Turnout 4.0 applied research project. The project focused on the development of an autonomous diagnostic system. A modular diagnostic system is described, including a sensor part installed on the crossing and the vehicle, data acquisition and storage in database systems, evaluation of signals by two systems – Train Identification System and Diagnostic Switches & Crossings – using artificial intelligence algorithms, Machine Learning and Bayesian statistical analysis. The extension of the system is the determination of the final score, describing the technical condition of the crossing, evaluating the score development over time, and displaying the monitoring results to the infrastructure manager.

Keywords: permanent-way, switches & crossings, autonomous diagnostic, artificial intelligence, machine learning, structural health monitoring.

1 Introduction

In 2020, the Turnout 4.0 project was launched. The project aims to adapt the conventional railway switch and crossing (S&C) structure to the fourth industrial technologies. The main objective was to develop an autonomous diagnostic system using installed sensors and Artificial Intelligence in the signal evaluation and, after that, sending a repair command before a fault occurs that could significantly affect rail traffic.

The project Turnout 4.0 participants were the Czech manufacturer of turnouts DT - Výhybkárna a strojírna, a.s., Brno University of Technology, University of Pardubice and RETIA, a.s. The first ideas for a S&C diagnostic device had already been formulated before the start of this project, during the Shift2Rail grant project with the acronym S-CODE (Switch and Crossing Optimal Design and Evaluation; www.s-code.info), of which the first three mentioned participants were also members of a broader international consortium. In this project, which dealt with radically new ways of designing switches and crossing structures, the first ideas on self-diagnosis and self-healing of turnouts were identified. As the topic seemed to be very promising, after the end of this project in 2019, a Czech consortium was subsequently established to follow up on the issues addressed, and with its project proposal, Turnout 4.0, succeeded in being awarded a grant in the first call of the Transport2020+ programme of the Technology Agency of the Czech Republic.

The activities in the project are mainly focused on developing an intelligent autonomous diagnostic system for turnouts [1]. The system is expected to be used both for conventional turnouts, which are used today in main lines, and prospectively also for turnouts installed in high-speed lines. Determining the operational condition of turnouts still needs to include using all existing scientific knowledge and technological developments. It relies primarily on experienced staff who use their expertise, manual measurements, and data from track recording cars to assess the condition of the turnouts and plan maintenance interventions. This process is quite demanding and time-consuming, involves risks associated with working on the track; the assessment is influenced by the subjective opinion of the responsible person, and with the possibility of automation, centralisation and prediction, it is more effective [2].

Many parameters describing the technical condition of the turnout are monitored by the railway staff manually on-site or by simple measuring devices. Some parameters can also be provided by more sophisticated track recording cars that regularly pass and measure the turnout. Diagnosing the condition of a turnout is mainly dependent on the human factor, on human understanding and previous experience, and often without the ability to make informed predictions for the development of potential faults. The system developed in the Turnout 4.0 project assumes a significant elimination of human activity on the turnout. This also looks to the future of railways. Such a diagnostic system will be essential for the future of the railways, because it will not be possible for employees of the infrastructure manager to enter the track of high-speed lines for routine inspection compared with the conventional lines.

A great importance in developing diagnostic equipment is put on the possibility of predictive detection of the turnout condition, which is not objectively possible with the current monitoring and measurement methods. Predictive maintenance, i.e., planned and targeted to a specific parameter in the turnout, means a significant cost saving for the manager, as these systems will be able to very efficiently plan the necessary maintenance interventions to minimise the need for track possessions and operation restrictions. Predictive maintenance will also mean significantly eliminating sudden failures, usually involving interruptions of several hours.

In the first phase, the project focused on identifying and predicting the following parameters. The wear of the critical parts of the turnout (i.e. moving switch rails and fixed crossing noses) and the condition of the track geometry in the turnout. As the moving part in the switch panel determines the direction of the train, the switch rails suffer from severe wear and material spalling near the switch toe where the wheelset is guided in the required direction. The crossing (especially the fixed crossing) is a critical part of turnouts, as it is where significant dynamic impacts occur; it can even be stated that, after eliminating the jointed track, it is the most critical location for dynamic load of the entire railway infrastructure. Therefore, the crossing panel is also very demanding to maintain, not only in terms of material wear but also due to the deterioration of the track geometry quality in this area. The project, therefore, aims to identify failures, particularly in the crossing panel. The aim is to optimally anticipate maintenance interventions such as grinding, welding, replacing the crossing, or track tamping (adjusting the track level) well in advance.

2 Diagnostic and Evaluation System

2.1 System Architecture

The basic principle for detecting and predicting the above-mentioned faults is sensing essential dynamic parameters at the rolling stock passage through the crossing using commercial or developed sensors. In addition to ensuring the acquisition, transfer and storage of measured data from each turnout, the major project activity is working with the recorded signals using advanced analytical methods – machine learning and neural networks. Once the signal has been evaluated, the information about the state of the turnout needs to be transferred to the end user – the railway infrastructure manager. Here, it is necessary to present the detected information about the state of the turnout in a suitable form and the possible need for maintenance intervention. This issue also needs to be solved within the framework of this project. The possibility of directly incorporating data presentation into the infrastructure manager's control systems is also considered. The aim is for infrastructure managers to see information within their system on the status of the crossing or entire turnout where this system has been implemented. Alternatively, it is also feasible to consider the possibility of the infrastructure manager providing the information available to him for the assessment of the turnout condition (e.g. selected data from track recording cars or information on maintenance interventions carried out on turnouts), which could contribute to the refinement of the analysis in the evaluation phase using autonomous evaluation algorithms.

The project does not only focus on a system where the infrastructure controls the infrastructure but also where the moving rolling stock asses the infrastructure using appropriate measuring devices. These devices capture characteristic dynamic parameters and relate them to specific turnouts on the rail network. The results of the primary processing of signals and measurement data are fed into the analysis by artificial intelligence (AI) algorithms, which are complemented by the Digital Twin system of the vehicle and turnout system.

The whole system includes the acquisition of turnout data, the database of measured data, processing by the evaluation system, the database of outputs and the display of results, see Figure 1. The system for acquiring data on a specific turnout includes measurements by sensors in the turnout, measurements by sensors on the special diagnostic vehicle or on in operation trains, a digital twin and measurements of turnout parameters with expert quantification of the turnout condition [3]. The amount of acquired data is organised in the DISC-S database systems for the in-track measurements, DISC-M for the on-vehicle measurements, DISC-S/M for the simulated results using the digital twin. For the structures to be monitored, it is necessary to have all parameters about the type and the structure itself, as well as all data from inspection activities or additional measurements and all maintenance interventions during the turnout's service life. The evaluation system consists of two parts, namely the TIS (Train Identification System) module [4] because there is a need to determine the specific vehicle in terms of its load and the IDIMASC evaluation module.

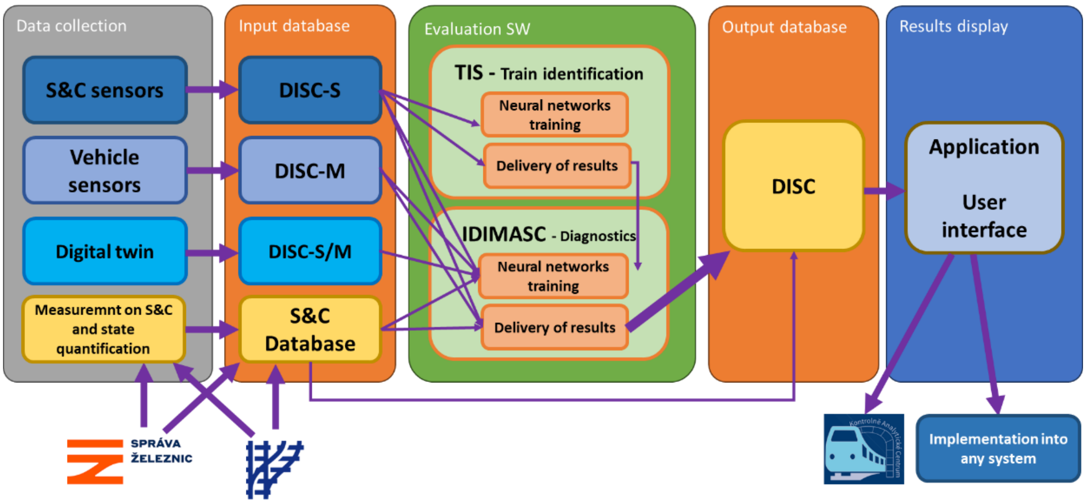

Figure 1: Basic architecture of the diagnostic system for evaluating the technical condition of switches and crossings.

Close cooperation with the Czech railway infrastructure manager was established in the project implementation process. However, due to the modular design of individual elements of the sensing, data transfer, evaluation and presentation process, it can also be assumed that the system can be adapted to other railway infrastructure managers.

2.2 Sensors and Associated Hardware

The sensors and their arrangement are the key elements of the whole system. A sensor system based on accelerometers and strain gauges has been designed to sense the vehicle's dynamic response during its passage. Both triaxial and uniaxial accelerometers were used. Both strain gauges and newly developed piezoelectric sensors were designed to sense strain. Piezoelectric sensors do not require a permanent power supply and are suitable for autonomous monitoring systems. Since the sensors are installed in areas where significant dynamic effects occur, the sensors had to be developed to withstand these hard conditions. It was also necessary to address the issue of sensor mounting, as it is impossible to drill holes in rails or sleepers, so it is best to use special glues to install the sensors. An example of the sensors assembly on a fixed crossing is shown in Figure 2.

A utility model protecting the developed ideal arrangement of the sensors in the crossing area has also been developed and applied. Individual positions were optimised for installing vibration acceleration and strain gauge sensors. The positions have been described in general terms for all crossing geometries; the layout is based on the position of the 26 mm and 40 mm crossing nose thicknesses where the wheel transition optimally occurs.

The developed sensors can also be installed in the switch part of the turnout or the crossing with the movable parts. In these areas, dynamic response is expected to be less significant, so the sensors should also be able to be used. Project Turnout 4.0 did not address the diagnostics of moving parts of the turnout in detail; this issue is expected to be addressed in a follow-up project.

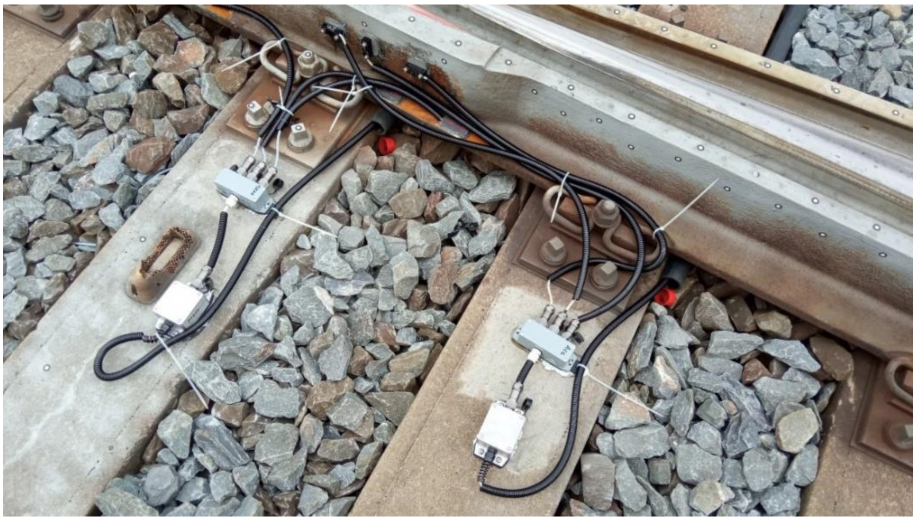

Figure 2: Positioning of measuring devices in the track with the hub and connected sensors.

The core part of the DISC-S device itself is the communication and control module. These two elements are installed in the box near the turnout diagnosed by the system. All installed sensors in the turnout are connected to the box. The aim was to make the device completely independent of the local electricity networks without needing an external power supply. This allows the device to be installed almost anywhere. Therefore, a solution was prepared with a power source (battery) and a solar panel to recharge the battery. From spring to autumn, this solution proves to be reasonably sufficient. In the future, the only issue that needs to be addressed is the power supply in winter, when there are occasional interruptions due to the shorter sunlight period. So far, the chosen testing turnouts have been fully equipped with sensors, including the control and communication module.

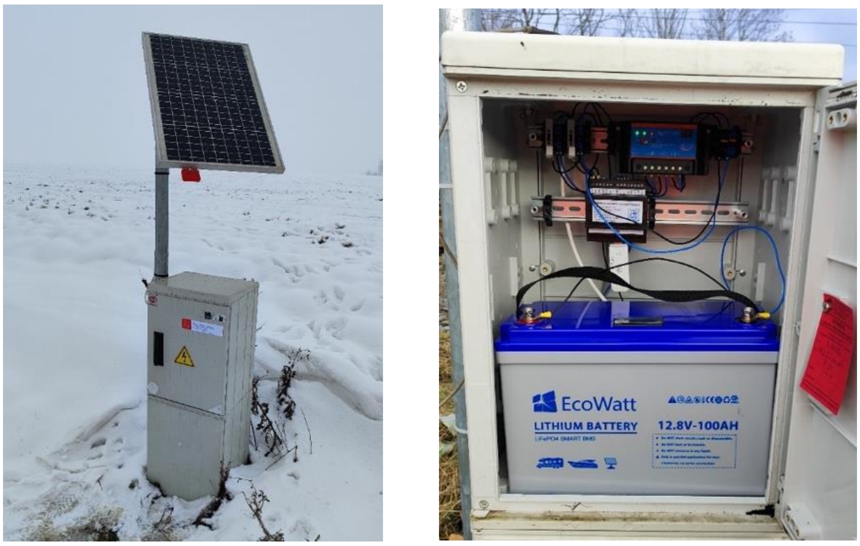

Figure 3: Control and communication module - overall view including solar panel (left) and view of the box interior (right).

The crossing state monitoring from the vehicle (part of the DISC-M autonomous measuring device [5]) is based on acceleration sensors mounted on the vehicle's unsprung mass. This device measures the dynamic response only at the switch points and sends the equivalent dynamic force information together with the metadata to a common database for ML evaluation. The further evaluation is then expected to use data from both the turnout and the vehicles.

2.3 Mathematical modelling of the turnout for identification of defects in the turnout

The dynamic calculations were analysed using the finite element method. The model of the turnout used for the calculations was created in the ANSYS software system. The 3D model consists mainly of spatial finite elements, see Figure 4 (left). This model is complex, including the switch itself and parts of the track grid in front of and behind the switch. Under the track is modelled ballast placed on a stabilisation layer. The lower layers are replaced by a flexible layer (Winkler's subsoil model). The turnout model is modular. The individual parts such as the plane line, the front, middle and rear part of the turnout, the switch point area and the crossing area can be used to create other turnout models. The dynamic interaction of the vehicle−turnout system is solved in such a way that the model of the turnout was combined with the model of the locomotive, see Figure 4 (right). This model incorporates important mechanical properties of the locomotive.

The axles are modelled, including wheelsets with suspension, as well as the joint connection of the chassis and vehicle body including suspension. The model includes the correct distribution of masses of vehicle parts and elastic and damping elements. Dummy engines, gearboxes and braking systems are modelled. The modelling is based on the drawing documentation. Clearances in the structural arrangement are considered in the model. The vehicle model in terms of mass distribution, stiffness of load-bearing elements and suspension is tuned to match the actual vehicle. To solve the dynamic response, the turnout model, including the vehicle model, was converted to LS-DYNA. This is a system for solving fast dynamic phenomena using explicit numerical integration methods. In this program, a series of calculations were carried out to drive the vehicle at different speeds. Defects in the turnout structure were modelled to determine changes in the dynamic behaviour of the turnout and the vehicle itself. These calculations can be used to complement and further analyse the results of measurements on the turnouts. The measured data corresponding to the acceleration response in the crossing region during train passage was analysed to obtain the response in velocities and in deflections, and these data were compared with the calculations. The calculations allow to obtain additional information about the behaviour of the switches that the measurements are not able to detect.

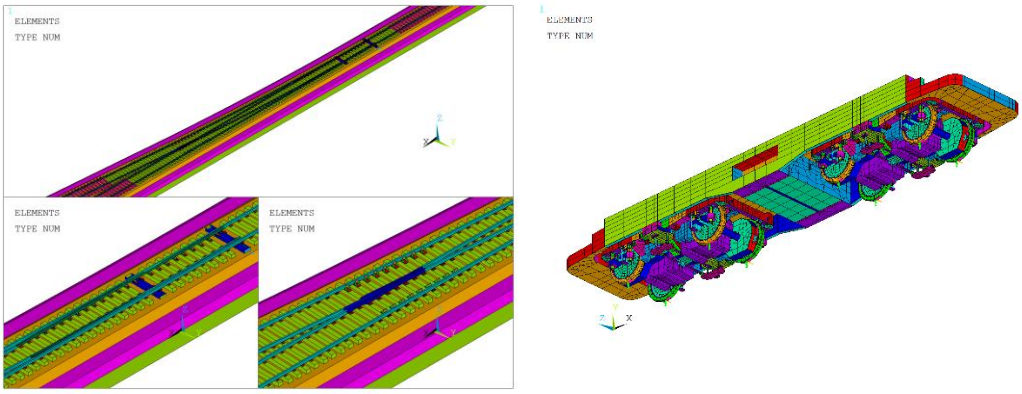

Figure 4: FEM model – Turnout (left); Locomotive (right).

3 Evaluation Results

3.1 System Architecture

In the context of on-track and on-vehicle data collection, it is expected that a large amount of data (Big Data) will be captured, which in principle cannot be evaluated manually. For this reason, autonomous evaluation software was developed to process the acquired data and provide information on the current technical condition of the turnout. During the evaluation process, it is not easy to interpret the measured vibration acceleration signals or the strain because the resulting phenomena represent the dynamic system of the track vehicle with many parameters that influence its behaviour. In addition to the technical condition of the turnout monitored, its structure and the structure of the entire superstructure and substructure, the time-varying loading of passing vehicles of different designs, axle weights of various technical conditions, etc., plays a crucial role. The response of the structure to these loads, recorded by the relevant sensors, is stochastic. The measured signals can then be evaluated in the time domain, e.g. through maximum or effective values, or they can be transformed into frequency spectra, and the behaviour can be investigated over a wide range of frequencies. Due to the random nature of these quantities, advanced statistical analyses must then be performed.

Considering the complexity of this process, it was decided to use Artificial Intelligence (AI) algorithms with Machine Learning (ML) support to evaluate the measured signals. The advantage of this approach is that there is no need to analyse the theoretical causal relationship between the technical condition of the turnout and the dynamic response captured by the sensors [6]. The AI algorithm is continuously trained to determine the technical condition of the crossing directly from the measured data.

3.2 Expert evaluation of crossing technical state

To learn an AI algorithm, it is necessary to specify output values for the training dataset. For this reason, it was essential to describe the technical state of the crossing panel under study. It was decided to quantify the technical state of the crossing by a relative index, a number in the range 0 – 1.0 (i.e., 0 to 100%), where a state of 1.0 represents a perfect technical state. It was necessary to quantify the technical condition of the monitored crossing panels, which was done by expert evaluation. This expert evaluation includes measurable parameters recorded during the standard as well as additional inspection of the turnouts during the measurement of track recording car. Additional measurements were geodetic levelling of the crossing panel and 3D scanning of the fixed crossing. A total of 30 parameters are monitored, then transformed concerning their limit values to relative values of 0.0 – 1.0 and their weighted average is calculated. The weights of each parameter were determined by a questionnaire to which experts from the Railway Administration, universities and turnout manufacturers responded. The technical condition of the turnouts determined by the expert evaluation is monitored over time.

The wear of the fixed crossing and the support of the sleepers influence the resulting vertical movement of the wheel and the associated force acting between the vehicle and the track. For this reason, in addition to the overall assessment of the condition of the turnouts from the measured vertical acceleration values on the vehicle, an analysis of the wheel/crossing contact in the vertical direction was performed and the vertical movement of the wheel (described as an angle of the trajectory) was included as one of the inputs to the expert assessment of the condition of the crossing. It is possible to detect and quantify the wear of the frog by contact measurement in defined sections (2D) or by a more advanced non-contact laser scan of the entire crossing part (3D), from which the 2D sections can be transformed to calculate the characteristics of the wheelset-track contact geometry (Figure 5).

In combination with the wheelset, it is thus possible to determine the geometrical vertical movement of the contact point on the relevant parts of the frog for a given lateral displacement of the wheelset in the track. The position of the contact points is related to the vertical motion of the wheel as it passes through the crossing part, from which it is possible to determine the longitudinal motion and contact angle 2α of the crossing [7], which affects the magnitude of the vertical forces P1 and P2 between the wheel and the rail.

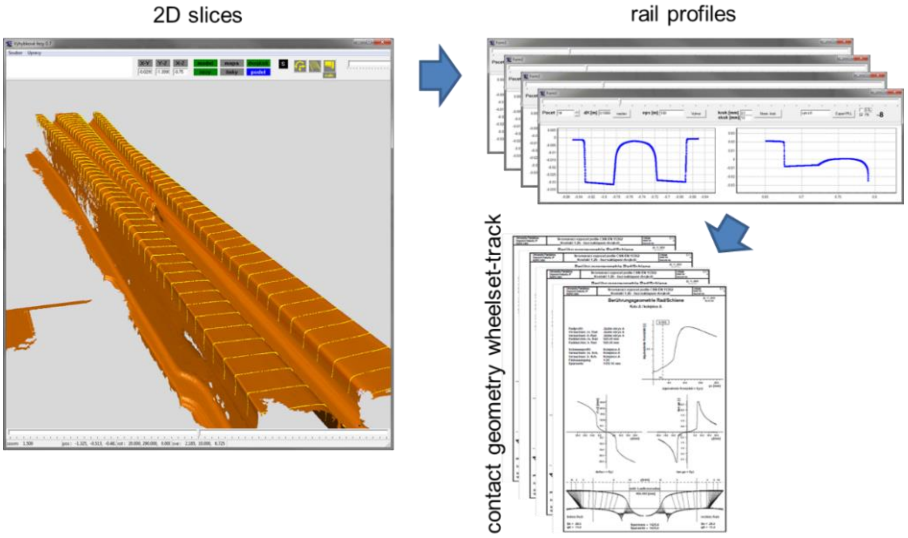

Figure 5: Example of the transformation of a scanned crossing part into sections and their use in the calculation of the characteristics of the wheelset-track contact geometry.

3.3 Algorithms using Artificial Intelligence

In the first phase of the signal evaluation from the sensors on the crossing, the series of the driving vehicle is first evaluated using the TIS system [4]. For this purpose, the system includes extraction of each signal to the part of the driving vehicle. A deep convolutional neural network has been proposed for locomotive-type recognition alone [8]. Subsequently, the state of the turnout is determined based on the measured acceleration signals using a trained IDIMASC machine learning model. A Random Forest regression model is used to determine the state of the turnout. This Machine-learning method combines many decision trees to produce a final index [3]. An example of the expert evaluation data used to train the model is shown in Figure 5.

In the next step, the estimated evolution in time is refined by the Bayesian statistics algorithm, where the scattered outputs of the AI algorithm are compared with the predicted values and an extrapolation of the evolution of the technical state of the turnout is proposed. An example of this processing is shown in Figure 6.

The assumed S-shaped degradation function can significantly enhance the extrapolation of the technical state of a railway crossing, particularly when only limited observed data within a narrow time window are available. This function models the degradation as a gradual process, with fixed tangents at the start and end of the crossing's service life, reflecting the initial slow wear, the rapid degradation during mid-life, and eventual stabilisation or rapid failure. Bayesian statistics can be employed to incorporate prior knowledge about the degradation process, allowing for predictions to be updated as new data is obtained. This approach facilitates the quantification of uncertainty in the extrapolations, resulting in more reliable long-term forecasts even when data is sparse.

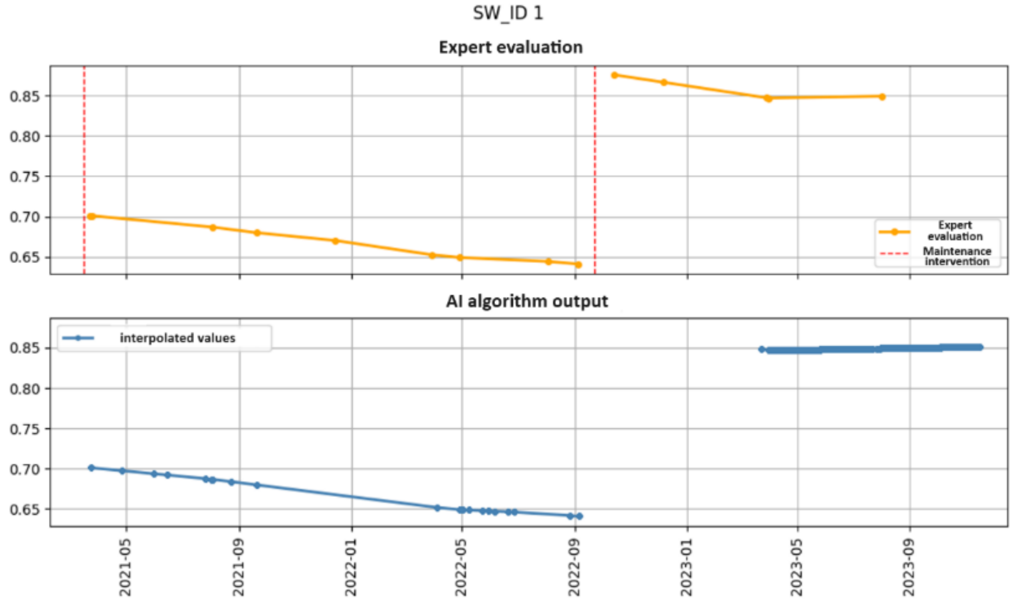

Figure 5: Example of comparison of the expert evaluation of a crossing and AI algorithm output.

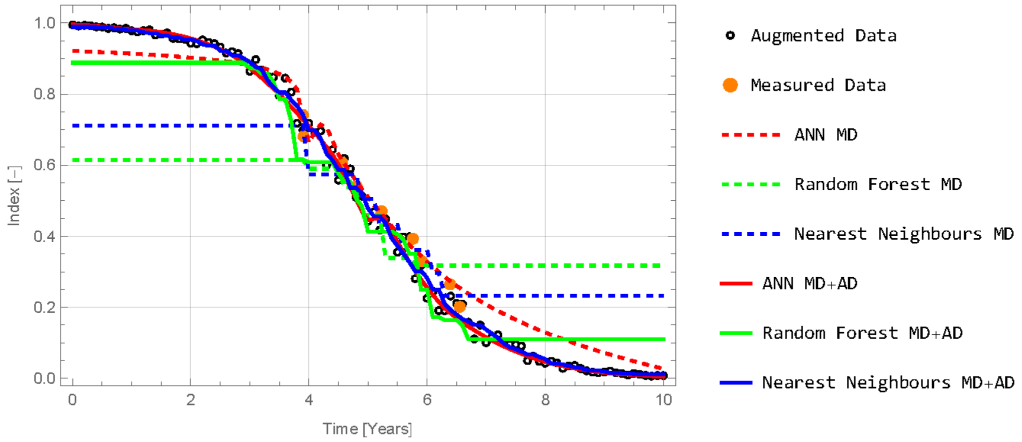

Figure 6: Extrapolation techniques utilizing measured and augmented data, where S-shaped Logistic (degradation) function is assumed to reduce the ambiguity and potential inaccuracy arising from limited range of measured data of the technical state of the crossing.

This approach enables the machine learning model to predict future states of the crossing more reliably, facilitating timely red-flagging of potential hazards, failures, or required maintenance, thereby improving overall safety and operational efficiency.

3.4 Interface for Infrastructure Manager

The data on the technical condition of the turnout, as assessed by measurements in the turnout and evaluated by software, must also be displayed appropriately to the infrastructure manager. The user interface has been designed as a web application; in this form, the results of the turnouts can be viewed by any staff member with the appropriate authorisation. For each turnout equipped with the diagnostic system, it is possible to monitor the evolution over time and, in case of significant deterioration of the technical condition, to carry out a local inspection, plan or directly implement a maintenance intervention.

A colour index helps to show the technical condition. Currently, the colours assigned to the turnouts are green – the turnout (crossing) is in good condition; orange, indicating a significant deterioration of the technical condition; and red, expressing the need for maintenance intervention. The determination of the specific range of values for individual turnout conditions was based on the Czech infrastructure manager's directives [9] and also on the Czech Technical Standard [10] in which three limits (AL – observation limit, IL – intervention limit and AIL – immediate intervention limit) are established. The green colour corresponds to the range from the nominal/production parameter values up to the parameter values corresponding to AL, orange for the parameter values corresponding to AL to IL and red for the parameter values IL to IAL, see Figure 7.

Figure 7: Colour index for expressing the technical condition of the turnout.

4 Conclusions and Contributions

The aim of the research and development work of the research team of the Turnout 4.0 project was to significantly contribute to increasing the reliability and safety of switch and crossing structures, reducing the costs of their maintenance, increasing the track availability by reduction of track possessions extent, reducing manual supervision activities and improving the objectivity of the evaluation of the technical condition of the structures, which is reflected in the achieved results of the project. The results achieved do not imply their immediate commercial application. The diagnostic system for turnouts will continue to be developed with a view to its application in commercially available turnouts. Similarly, follow-up projects will extend the development to the turnout replacement part.

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