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Modeling switch rail wear using laser profilometry for predictive maintenance

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ABSTRACT

The safe and uninterrupted operation of trains through railway turnouts depends significantly on the reliability and maintenance of track infrastructure, particularly in critical components such as switch and stock rails. This study presents the results of innovative field measurements conducted using a laser profilometer to assess vertical and lateral wear in operating turnouts subjected primarily to passenger traffic. The experiment was performed on a commonly used 60E1-500 turnout configuration under real traffic conditions, with rolling stock axle loads totaling 18 teragrams (Tg) and 27 Tg, respectively. The primary aim of the research is to develop a predictive framework for the degradation of turnout rails by correlating empirical wear measurements with specific operational parameters, such as axle load accumulation, switch geometry, and accessibility for tamping. By utilizing high-resolution cross-sectional rail profiles and examining wear distribution along the length of the curved switch rail, the study identifies areas most susceptible to premature degradation – particularly near locking devices where maintenance access is restricted. The novelty of this work lies in its integration of profilometric data into a predictive diagnostics context, which enhances the capability for proactive infrastructure maintenance and reduces dependence on manual inspections. The methodology and findings presented in this paper offer a scalable diagnostic model applicable to both conventional and high-speed rail systems, paving the way for data-driven asset management strategies across railway networks. The measured vertical wear reached up to 2.9 mm near the locking device area, while lateral wear exceeded 1.8 mm at critical cross-sections. These values confirm the location-dependent degradation and validate the measurement approach.

Keywords: railway infrastructure, turnouts, measurements, track maintenance

INTRODUCTION

The availability of railway infrastructure is a cornerstone of efficient and reliable train operation. According to the European standard EN 50126 [1], availability is defined as the "ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided." As illustrated in Figure 1, turnout availability is not only a function of technical condition but also of effective coordination between infrastructure, maintenance processes, and traffic control systems.

Alongside punctuality, availability is one of the most frequently reported performance indicators in the railway sector and is regularly documented in public reports, including those published by the Polish Office of Rail Transport (Urząd Transportu Kolejowego) [2]. It reflects the combined effects of infrastructure design, traffic density, operational loads, and the quality and timing of maintenance interventions.

Railway turnouts – essential components that enable directional changes of rolling stock – represent one of the most mechanically complex and wear-prone parts of the track system. Their proper functioning relies on high mechanical

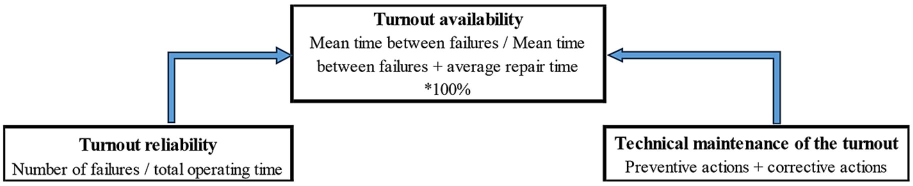


Figure 1. Turnout availability

precision and continuous monitoring of wear in critical components, particularly the stock and switch rails. Traditionally, maintenance strategies for turnouts have relied on fixed-interval inspections and reactive interventions. However, recent years have seen a paradigm shift toward predictive maintenance, supported by the development of diagnostic tools and data-driven decision models.

Preventing infrastructure failures at turnouts is vital for both safety and availability. As outlined in prior European research [3], operational faults in switches and crossings (S&C) account for a significant share of infrastructure-related disruptions. These faults are often initiated by wear accumulation, contact fatigue, or geometric misalignments, especially under high-frequency loads in heavily trafficked lines.

Despite increasing use of condition monitoring technologies, real-world diagnostics often suffer from limited spatial resolution and insufficient contextualization. For example, the early identification of vertical and lateral wear in switch rails – particularly in curved configurations – remains a challenge due to variability in axle loads, substructure stiffness, and seasonal conditions (e.g., heating efficiency in winter). In this context, even localized degradation near locking devices may result in disproportionate operational risks.

Furthermore, the railway sector faces a growing shortage of qualified maintenance personnel and diagnostic engineers. This generational gap complicates the interpretation of field data and limits the effectiveness of visual inspections. Therefore, new diagnostic approaches are required that can capture fine-grained wear patterns while integrating key operational parameters such as load history, traffic direction, tamping efficiency, and geometric design.

This paper addresses these gaps by presenting field-based research using high-resolution laser profilometer measurements of switch and stock rail profiles. The case study focuses on the 60E1-500-1:12 turnout geometry, which is representative of current infrastructure on Polish passenger lines. The research analyzes vertical and lateral wear progression at various stages of traffic load accumulation (18 Tg and 27 Tg), taking into account maintenance constraints and localized geometrical effects.

The aim of this research is to quantify and model wear behavior in turnout rails under defined operational conditions. Particular attention is paid to identifying zones of intensified degradation, such as those adjacent to locking devices or exhibiting asymmetric loading patterns. The novelty of this study lies in its systematic application of profilometric diagnostics to turnout switches and its potential to inform predictive maintenance models. This approach has practical implications for turnout lifecycle management, safety enhancement, and budget optimization in both conventional and high-speed rail systems.

Turnouts on the railway network

Railway turnouts constitute a significant part of the entire railway line in Poland. In 2023, the length of railway lines in operation was over 18.806 km, which is over 36.326 km of track. Within the operated railway lines of PKP Polskie Linie Kolejowe, there are 37.352 turnouts [4]. The total length of turnouts in the entire infrastructure can be written with the following Equation 1.

$$lSR = \beta \times lR \tag{1}$$

where: l_{SR} – total length of turnouts in PKP PLK SA lines, β – coefficient depending on the geometry of the turnout, l_R – length of turnout.

For the purposes of determining the percentage share of turnouts in the length of the railway line, the authors assumed that the turnout length would reflect the most frequently used turnout geometry type 60E1-300-1:9 with a total length of 32,540 mm. The above can be converted to equivalent track length using the following Equation 2.

$$\Delta = \frac{32.54 \times 37352}{36326000} \times 100\% \tag{2}$$

where: Δ – percentage share of turnouts in railway lines.

In connection with the above calculations, the degradation of the turnout, including the rolling surfaces, is a significant, negative phenomenon occurring in the track and causes a gradual loss of functional properties, which may occur during:
a) full operational fitness Z_p,
b) limited operational fitness Z_o,
c) unfit for operational Z_n.

Unlike railway traffic control systems, where the system is either fit or unfit, turnout degradation is characterized by an intermediate state. Each of the three presented phases of exploitation Z_p, Z_o and Z_n, is a set of operating speeds depending on the railway infrastructure condition [5]. The formula can be denoted as shown in Equation 3.

$$\left.\begin{array}{c} \dfrac{Ve}{Vmax} = 1 \;\rightarrow\; Z_p; \\ 0 < \dfrac{Ve}{Vmax} < 1 \rightarrow Z_o; \\ \dfrac{Ve}{Vmax} = 0 \rightarrow Z_n \end{array}\right\} \tag{3}$$

where: V_e – operating speed, ($V_e \leq V_{max}$),
V_{max} – maximum operating speed, therefore, a distinction must be made between the degradation state of a railway turnout and the transition from Z_p to Z_n, so failure. The relative wear Z_w of the rolling elements of the turnout during operation is defined as the ratio, as shown in Equation 4.

$$Z_w = \frac{Z}{Z_g} \tag{4}$$

where: Z – measured wear after passing the load,
Z_g – maximum allowable wear.

When the maximum allowable wear may be specified in track maintenance instructions or technical standards issued by the rail infrastructure manager and is usually expressed in mm. As stated in the instructions Id-4 [6], maximum vertical wear of the switch rail in the main tracks is 8 mm and the maximum lateral wear of the switch rails that qualifies for replacement is 10 mm, provided that the track gauge tolerance is not exceeded within the switch section. An additional important parameter is the lateral wear angle measured at a height of 5 mm and 15 mm from the rail head and cannot exceed 30° for main lines as shown in Figure 2.

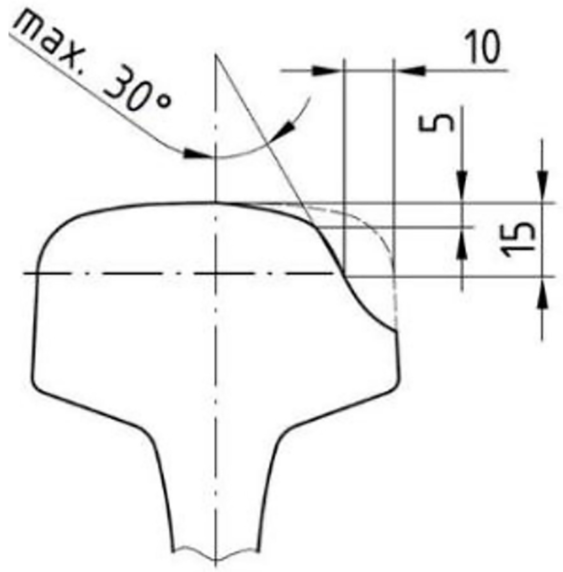


Figure 2. Maximum wear of turnout rail elements [6]

Railway turnout

The turnout consists of 3 sections: switch with locking devices, closure rails and crossing with guard rails for conventional railway lines [7, 8]. The geometric layout of the turnout is shown in Figure 3, while the basic construction and geometric parameters characterizing the tested simple turnout type 60E1-500-1:12 sb 1:40 1435 mm are presented in Table 1 as, among others [9, 10]:
a) 60E1 – type of rail profile [11],
b) 500 – radius of diverging track,
c) 1:12 – angle,
d) s – welded version,
e) b – assembled on prestressed concrete sleepers,
f) 1:40 – rail inclination,
g) 1435 – track gauge.

Construction and components of the switch section

The basic task of a switch section is to be able to change the direction of travel of the rolling stock from the main track to the diverging track [12, 13]. The operation is carried out by means of movable elements of the switch, which are a straight switch rail and a curved switch rail [14]. The change of the switch rails position from the closed to the open position is carried out using the point machine via the locking devices [15]. Depending on the turnout radius, the switch may be equipped with one or multiple locking devices [16]. In the tested turnout, the switch was equipped with two locking devices.

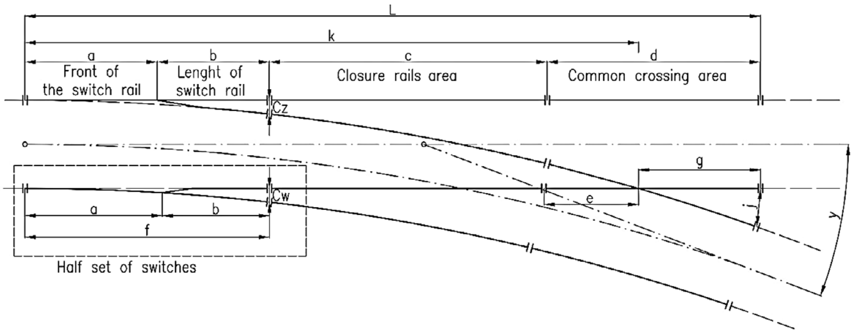


Figure 3. Geometric layout of the turnout type 60E1-500-1:12

The influence of rolling stock on the turnout

The parameters characterizing the influence of the rolling stock on the turnout buckling are the vertical force Q and the lateral force Y coming from the rolling stock wheel on the rail head. The ratio of the $\frac{Y}{Q}$ values is called the derailment coefficient, which characterizes the potential climbing of a rail vehicle wheel onto the rail head and is largely dependent on the coefficient of friction between the wheel and the rail profile and on the outer contour of the wheels. According to European standards, driving safety is ensured when the coefficient, also known as the Nadal formula, meets the condition, as shown in Eq. (5), [5].

$$\frac{Y}{Q} = \frac{tg\alpha - \mu}{1 + tg\alpha \cdot \mu} < 1.2 \quad (5)$$

where: α – wheel flange angle equal 70°, μ – coefficient of friction between wheel and rail equal to 0.36.

Currently, attempts are underway to modify Nadal's formula by using 3D wheel-rail models together with simulations of the sinusoidal motion of a rail vehicle moving through a turnout, particularly in the movement onto the diverging track.

MATERIALS AND METHODS

Field test of operational wear of switch rails

The previous theoretical analysis as well as the conducted research and computer simulations are burdened with a number of simplifications, including: dynamic impact of the vehicle on the turnout depending on the quality of the railway track tamping, movement of both switch rails in the vertical and horizontal directions during the passage of the rolling stock through the turnout and the estimated average maximum speed for a given railway line.

Observing the development of damage to the rail infrastructure along with the measurements taken is currently the basic method of monitoring the technical condition of the railway track in use. In order to accurately assess the technical condition of the turnout and predict potential future changes occurring in the product life cycle, it is necessary to implement diagnostics of the places most exposed to damage and contact-fatigue defects. The operating costs of turnouts throughout their entire life cycle largely depend on meeting these conditions, the main factor of which is the expenditure on repairing or replacing the track infrastructure. The evaluation of the turnout degradation during operation is presented in Figure 4.

Statistically, the intensity function $\lambda(t)$ describes the ratio of the number of failures per unit of time to the total number of undamaged elements up to a given moment, as shown in Equation 6.

$$\lambda(t) = \frac{\Delta n}{\Delta t} \cdot \frac{1}{n(t)} \quad (6)$$

where: Δn – damage growth in time period Δt, $n(t)$ – number of items undamaged until time t.

The basic costs include:
a) Preventive actions (preventive repairs, often indicated by the manufacturer after a specified period of operation or after passing trains with a specified mass Tg – teragram, equivalent to 1 million metric tonnes),
b) Corrective actions (actions independent of manufacturer guidelines, constitute the highest cost in case of limiting rail traffic).

The latest trend based on the use of artificial intelligence discussed in the literature on the subject [17, 18] is the issue of the next action, i.e.

Table 1. Geometric dimensions of the turnout type 60E1-500-1:12

Turnout 60E-500-1:12			
a – front of the switch rail	2165 mm	f – half set of switches	17640 mm
b – length of the switch rail	15475 mm	g – frog hell length	3713 mm
Cz – outside half switch spread	311 mm	h – frog toe spread	308 mm
Cw – inside half switch spread	311 mm	j – frog hell spread	294.5 mm
c – closure rails area	15925 mm	k – turnout length to frog point	37881.4 mm
d – common crossing area	8036 mm	L – turnout total length	41594.6 mm
e – frog toe length	4320 mm	γ – turnout angle	4° 45’ 49.11”

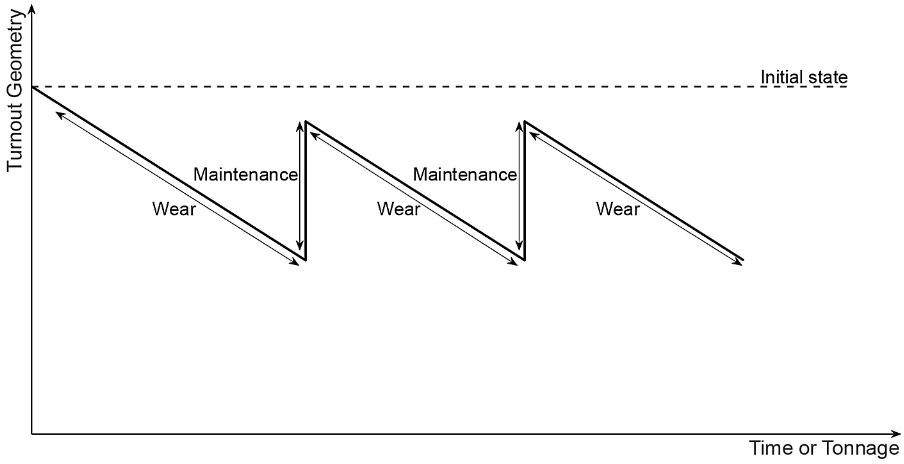


Figure 4. Track degradation and maintenance

predictive maintenance based on predictions, most often resulting from the analysis of trends in defect progress or track-rolling stock interactions.

Transitions between a minor fault and a derailment hazard most often occur due to failure to detect the fault in its early stages of development or failure to perform appropriate preventive or corrective maintenance. A typical example, often occurring in railway lines, is the vertical and lateral wear of the stock rail profile and the switch rail profile at the point with its the smallest cross-section, also in the area of cooperation with the locking device. Failure to detect or neglect actions at the initial stage of defect development results in increased impact of the rolling stock on the stock rail in the switch, which in turn leads to flow of stock rail material and further negative impact on the switch rails. The consequence of the previous actions is the lack of contact between the closed switch rail to the stock rail and the potential lack of contact between the switch rail and distance block. The above causes a lack of train movement stability with a tendency for lateral displacement of the rolling stock bogies and consequently the wheel flange gets caught on the blade of the switch rail. As a result, the switch rail will suffer breakouts, which will have a negative impact on the cooperation of the switch with the turnout point machine and can be a potential risk of derailment of the rolling stock. The sequence of steps is shown in Figure 5.

An example of fatigue-related damage in the form of material flow and breakouts in the switch rail zone is presented in Figure 6, where typical symptoms of rolling contact fatigue (RCF) are visible. These include surface cracking, localized plastic deformation, and disruption of the rail profile continuity. Such defects lead to the loss of proper geometric alignment between the switch and stock rails, potentially resulting in poor closure, loss of contact with spacer blocks, and increased derailment risk if not detected and addressed through preventive maintenance.

Progressive wear and contact fatigue of the stock and switch rails may lead to deterioration in key geometric features, affecting the turnout’s ability to maintain tight closure and safe positioning. Faults in the steel elements of the switch

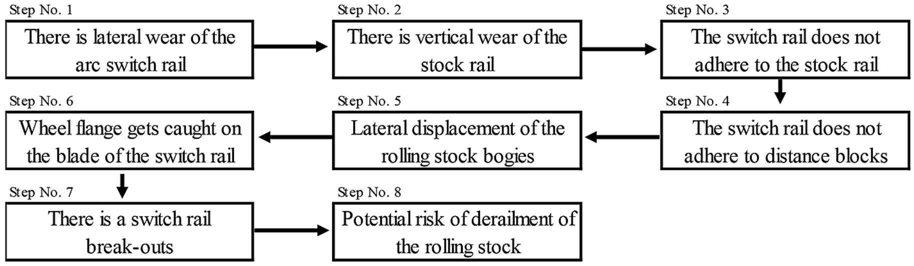


Figure 5. Development of damage from a minor defect to derailment of the rolling stock

mechanism can interfere with components such as point machines or detectors, potentially producing incorrect signals related to switch rail position.

One of the key observed damage mechanisms is contact fatigue, visible as material flow and local spalling in the switch rail zone. These failures, if not identified in the early stages, escalate the lateral forces exerted by the wheels, leading to severe plastic deformation of the stock rail and further impacting the switch rail condition. This can ultimately result in poor closure of the switch rail, loss of contact with spacer blocks, and cracking or fragmenting of the switch tip – all contributing to derailment risk.

Similar defects have been widely reported in the literature. Grossoni et al. [19] confirm that "lipping" (plastic deformation of switch rails due to repeated impact) is the most frequently observed failure in switch panels, accounting for 47% of cases in their 7-year GB network analysis. They also classify spalling and squats as key manifestations of rolling contact fatigue (RCF) in switch and crossing panels.

The theoretical foundations for fatigue crack initiation due to material inclusions and internal defects are well described by Zerbst and Klinger [20], who highlight how cyclic stresses and material discontinuities lead to sub-surface crack formation and eventual fracture.

Moreover, Yuan et al. [21] demonstrate that vibration-induced fatigue in non-contact zones, such as the web and foot of point rails, contributes to degradation under dynamic loading. Their results show a 36% reduction in fatigue life at higher operational speeds, emphasizing the importance of holistic diagnostics that consider both contact and non-contact fatigue.

These findings confirm that the observed material flow and cracking in this study are consistent with known failure modes in modern railway turnout systems and reinforce the need for predictive diagnostics based on fatigue-prone areas.

One of the methods for tracking the development of damage is condition monitoring system, which can occur sequentially at defined time intervals or continuously [22, 23]. Continuous monitoring of turnouts in operation is currently in the initial phase of implementation by turnout manufacturers and focuses on sensors installed near the turnout point machine [24, 25]. These systems aim to provide real-time condition data and early failure detection. Additional approaches, including hybrid diagnostic models and monitoring curve segmentation, have also been explored [26].

In contrast, sequential monitoring of turnouts most often involves regular inspections performed by maintenance services. These are carried out using dedicated control and measurement tools, such as the electronic track gauge shown in Figure 7 [27, 28]. Furthermore, inspections may also be conducted using specialized diagnostic vehicles, such as those shown in Figure 8 [29].

EXPERIMENTAL FIELD TEST OF SWITCH WEAR

The method of testing the wear of rails in the switch, including the profile of the stock rail and the profile of the switch rail, was developed on the common turnout type 60E1-500. The tests were carried out using a laser rail head profilometer "Railprofile 2D" SN005/23, manufactured by P.U.T Graw, along with data analysis in the software Dari®. The device is shown in Figure 9. Experimental field tests was carried out on the double-track railway line no. 91, Kraków Główny – Medyka, which is shown in Figure 10. For research purposes, the following assumptions were made:
- the rolling stock moves on the blade of the switch rail,
- the rolling stock moves from the blade of the switch rail,

Figure 6. Example of breakouts on the switch rail

Figure 7. Digital track guage

Figure 8. Diagnostic vehicle type DP-560.00 no. 01

- the new switch is the reference base,
- tests were carried out after the load had passed: 18 Tg and 27 Tg,
- the speed of the railway vehicles: 100 km/h and 160 km/h,
- tested section of the switch from the blade of switch rail in the range from 0 mm to 3000 mm,
- tested cross-sections of the switch every 50 mm,
- profile of the stock rail 60E1, profile of the switch rail 60E1A1 [11].

These assumptions form the basis for the model for testing the wear of rail profiles in the switch type 60E1-500, constitute the basis for drawing conclusions from the measured results in the operation of turnouts, taking into account the impact on the curved elements of the turnout. The research results will be a precursor to building a database for the development of predictive diagnostics in the operation and maintenance of rail infrastructure for conventional railway lines and, in subsequent steps, also for high-speed railway lines. The cross-sections of the new half a set of switches, which is the reference base for the measurements, are shown in Figure 11 with the locations of the tested places every 200 mm from the blade of the switch rail.

Cross-sectional profiles were taken along the length of the switch rail at defined intervals to

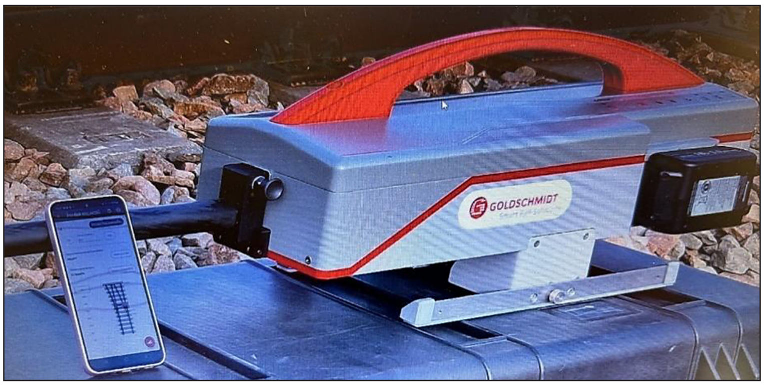


Figure 9. Laser profilometer „*Railprofile 2D*" SN005/23

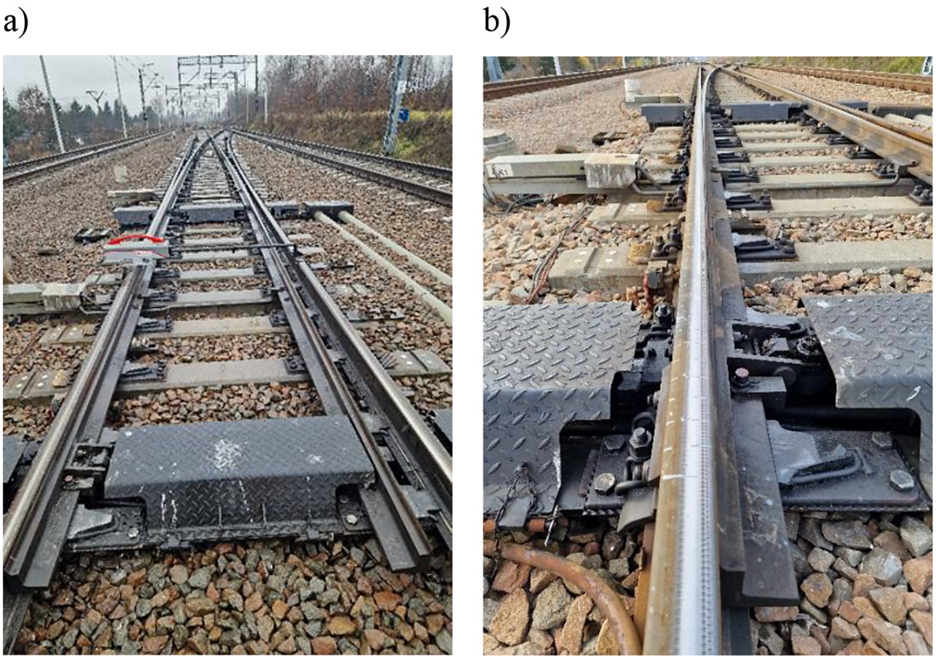


Figure 10. Tested switch: a) measurement of the curved switch rail, b) measurement locations

capture vertical and lateral wear. The position of each measurement is expressed in Figure 11 as 'x', which indicates the distance from the beginning of the switch rail, measured in millimetres.

RESULTS

The experimental field tests were carried out in 2024 and 2025 on a turnout type 60E1-500, where switch include two locking devices. The tests of wear of the turnout rail elements were carried out after the total passing of the rolling stock mass: 18 Tg and 27 Tg and concerned the following geometric parameters:
a) track gauge,
b) track cant,
c) track twist and
d) laser measurement of rail head profile wear.

The track gauge check was used to evaluate subsequent measurements, and the track twist parameter was measured as the difference in rail cants measured in two cross-sections spaced apart by the length of the adopted measurement base of 5 m [30], as shown in Equation 7.

$$W = (n1 - n2) - (n3 - n4) \quad (7)$$

where: W – track twist, n – track cant.

The results of track cant and track twist are presented in Table 2, while the results of operational wear starting from the blade of switch rail in the range of every 200 mm are presented in Table 3.

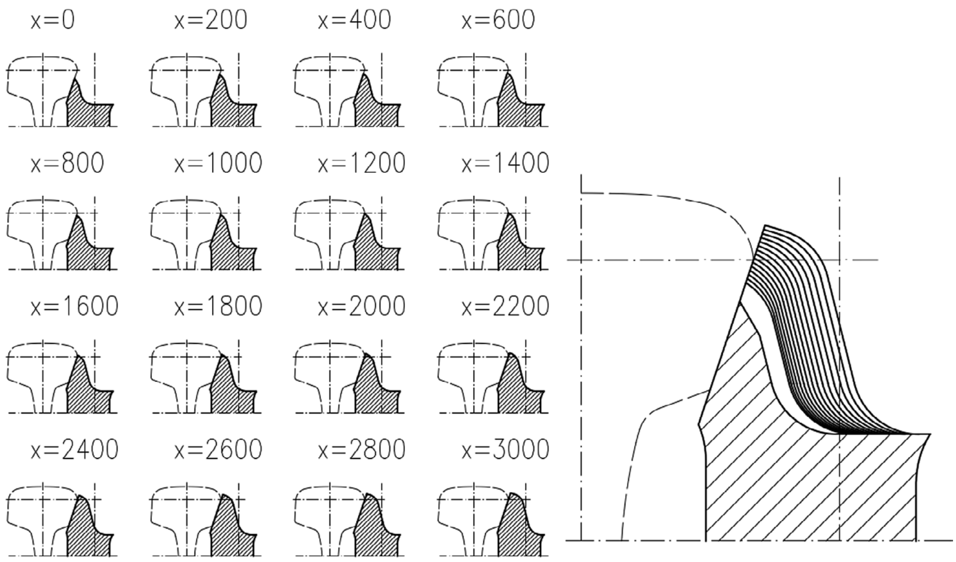


Figure 11. The cross-sections of the new half set of switches type 60E1-500

The dash symbol (-) in the "Rail profile inclination angle [°]" column indicates that the rail profile inclination angle could not be determined in this region due to the insufficient length of the measured switch rail cross-section (0–1200 mm). In this zone, the lateral wear geometry does not provide enough data to calculate a reliable angle using the standard reference heights (5 mm and 15 mm).

Summary of observations: Wear tends to increase progressively from the blade tip along the curved switch rail. Notably, higher wear values appear near the first locking device – likely due to restricted tamping access. These localized effects suggest the need to factor tamping accessibility into predictive wear modelling.

The distribution of vertical wear of half-set switches rails in the operated turnout after passing a rolling stock with a total weight: 18 Tg and 27 Tg is shown in Figure 12.

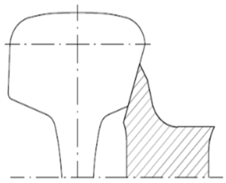
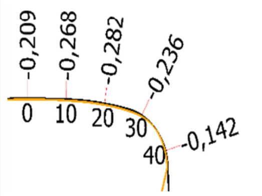
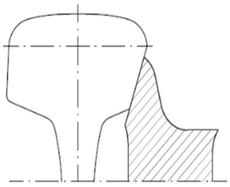
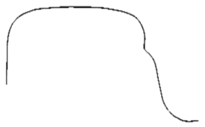
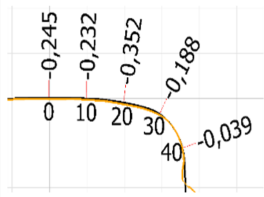
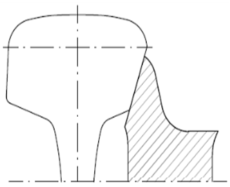
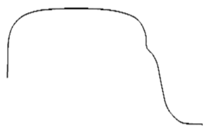
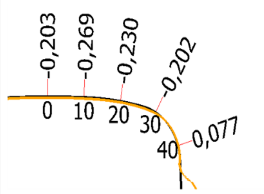
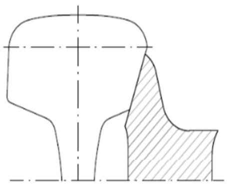
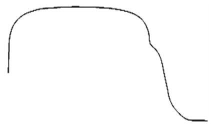
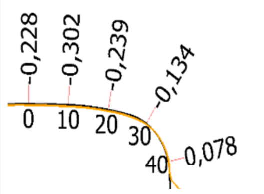
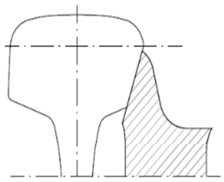
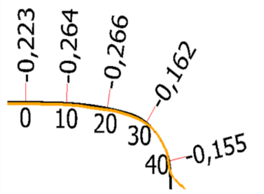
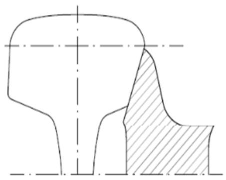
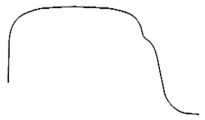
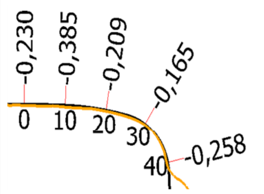
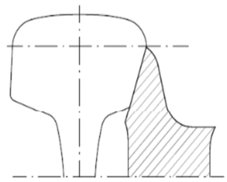
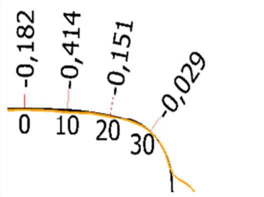
The lateral wear angles were calculated directly from laser profile measurements at heights of 5 mm and 15 mm from the railhead, in accordance with standards specified in [6].

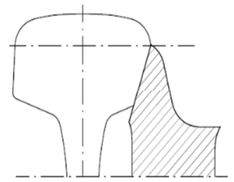
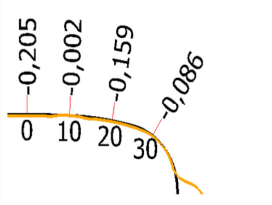
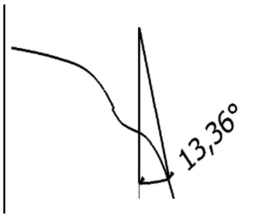
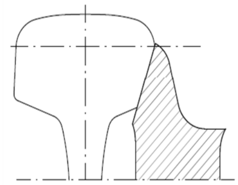
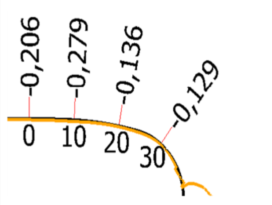
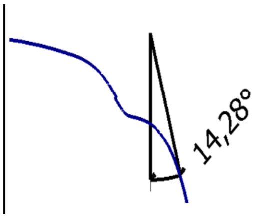
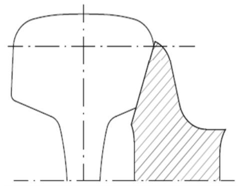
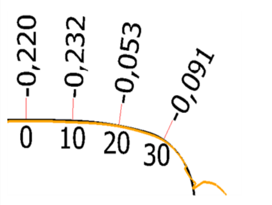
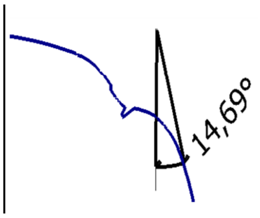
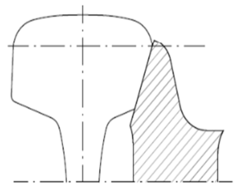
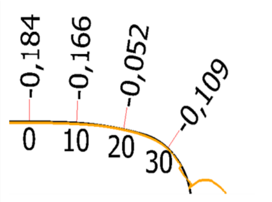
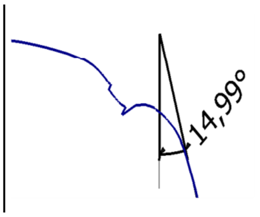
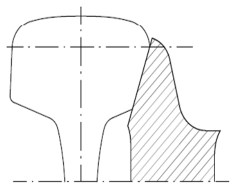
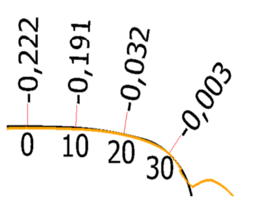
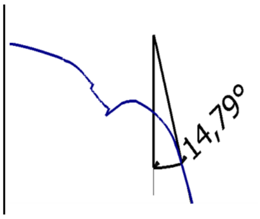
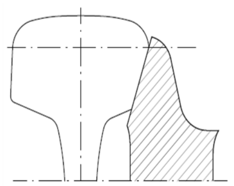
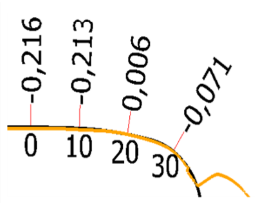
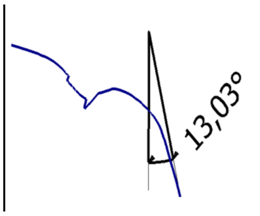
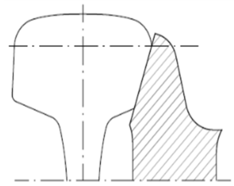
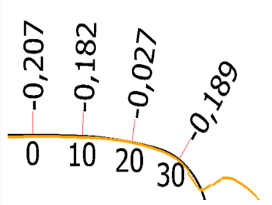
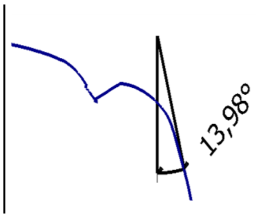
The results of field tests confirmed the good condition of the rail infrastructure in terms of operation and technical maintenance, which affects the high availability of rail traffic. The measurement results after passing a rolling stock with a total weight: 18 Tg and 27 Tg, show the dependence of the wear of rail elements on the sum of the masses (tonnage) of the trains passing through the turnout. Based on the conducted field tests, it is possible to program further wear of rail sections and work related to preventive maintenance of the railway infrastructure. The analysis of the measurements and the graphs from the conducted tests show the dependencies and trends on the annual loads of the railway line and the layout and geometry of the turnout, and thus a greater vertical wear is noticeable in the area of 1 locking device, which may be directly caused by lower accessibility in the tamping of this section of the turnout [31, 32]. Another important parameter is the lateral wear angle of the switch rail measured according to Figure 2, which increases with the increase of the switch rail cross-section, but the

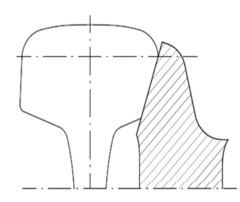
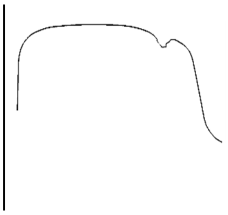
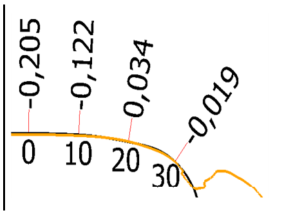
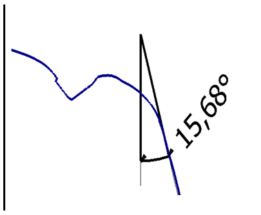
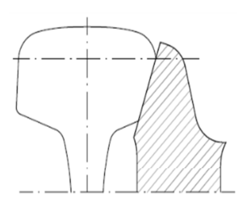
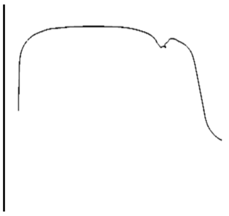
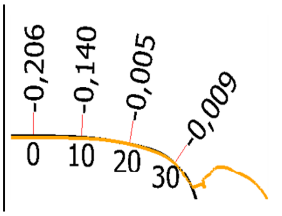
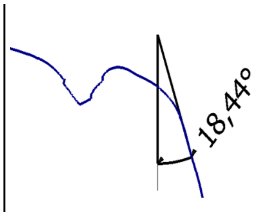
Table 2. Track cant and track twist results on the switch type 60E1-500

No	Place	Cant	Twist	Remarks – place
	[m]	„n" [mm]	„W" [mm]	
1	-10	-0.7	-	Front of the switch rail
2	-5	-0.9	0.2	Front of the switch rail
3	0	-0.1	-0.8	Start of the switch rail
4	5	-2.2	2.1	Switch rail
5	10	-1.8	0.4	Switch rail

Table 3. Results of field tests of the switch 60E1-500

Mode no.	Distance from the start of the switch rail	Cross-sections for the new switch	Cross-sections of the half switch after 27 [Tg] load	Dimension difference – from the rolling rail side (wear)	Rail profile inclination angle
	[mm]			[mm]	[°]
1	0				-
2	200				-
3	400				-
4	600				-
5	800				-
6	1000				-
7	1200				-

Mode no.	Distance from the start of the switch rail	Cross-sections for the new switch	Cross-sections of the half switch after 27 [Tg] load	Dimension difference – from the rolling rail side (wear)	Rail profile inclination angle
	[mm]			[mm]	[°]
8	1400				
9	1600				
10	1800				
11	2000				
12	2200				
13	2400				
14	2600				

Mode no.	Distance from the start of the switch rail	Cross-sections for the new switch	Cross-sections of the half switch after 27 [Tg] load	Dimension difference – from the rolling rail side (wear)	Rail profile inclination angle
	[mm]			[mm]	[°]
15	2800				
16	3000				

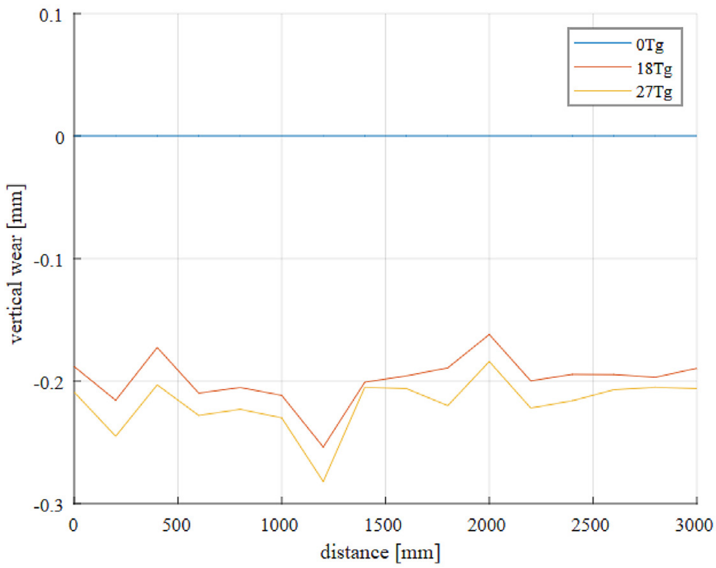


Figure 12. Vertical wear of switch rails type 60E1-500

measured results are far from the maximum permissible operating parameters.

DISCUSSION

The field test results provide strong evidence of measurable, repeatable patterns in the operational degradation of turnout switch rails. The laser profilometer-based approach enabled precise identification of vertical and lateral wear trends, particularly in zones influenced by operational constraints and maintenance limitations. The observed concentration of wear near the first locking device corroborates known issues with tamping access and increased dynamic forces in this critical transition area.

Additionally, asymmetric wear between left-hand and right-hand switch rails was observed, consistent with variations in vehicle approach direction and wheel–rail contact geometry. Such asymmetries have been noted in previous studies, including those analyzing wheelset steering behavior and its influence on rolling contact fatigue.

A significant finding is the correlation between cumulative tonnage load and wear depth.

After 27 Tg of operational load, compared with measurements at 18 Tg, degradation patterns intensified substantially. This indicates that wear accumulation follows a nonlinear trend, possibly accelerating under poor maintenance or high-load scenarios.

The types of damage observed – such as material flow, plastic deformation, and spalling – are characteristic of rolling contact fatigue (RCF) and have been extensively documented in both laboratory and real-world investigations. Our findings confirm the presence of early-stage RCF symptoms, including surface irregularities and side wear, particularly in the curved portions of the switch rails.

These insights underscore the importance of moving from scheduled to condition-based or predictive maintenance strategies. The data presented here demonstrate that profilometric measurements can serve not only as diagnostic tools but also as input for long-term predictive modeling. As such, they may facilitate the shift toward data-driven asset management, enabling infrastructure managers to optimize inspection intervals and reduce lifecycle costs.

In the context of railway safety, this research highlights the persistent risk factors associated with turnout operation under variable load and maintenance quality. Incorporating such empirical findings into turnout lifecycle management systems will be essential for enhancing operational reliability on high-traffic corridors.

Compared to other data-driven approaches in the literature, such as the regression-based model proposed by Vale et al. [18] for predicting overall track condition or the machine learning frameworks surveyed by Xie et al. [17], the predictive method presented in this study is tailored specifically to the geometry of switch rails and localized degradation patterns. While general track degradation models often rely on aggregated indicators (e.g., roughness or ride comfort), the present model utilizes high-resolution profilometric inputs, which provide precise geometric insights for targeted maintenance planning.

CONCLUSIONS

An important contribution of this research is the development of a conceptual basis for a predictive maintenance model. Based on the laser profilometer measurements and wear accumulation trends, the model integrates key operational parameters such as cumulative axle load, traffic direction, switch rail geometry, tamping condition, and environmental factors like winter heating performance. These inputs are intended to feed into a regression-based predictive algorithm, which can be refined using machine learning techniques when historical data become sufficiently available.

The envisioned model will estimate the time or tonnage until maintenance thresholds are reached in specific zones of the turnout, particularly near locking devices and curved rail sections prone to contact fatigue. By leveraging profilometric data as a high-resolution diagnostic input, the model aims to reduce dependency on manual inspections and support condition-based decision-making. Future work will include calibration of the model against extended operational datasets and validation through comparative studies across multiple turnout configurations.

The conducted research confirms the relevance of the 60E1-500 turnout type as a representative element of the national railway infrastructure, particularly in mainline segments characterized by intensive train movement. The large number of turnouts of this type in use makes it a practical reference point for diagnostic and wear studies.

Field tests performed on the Kraków Główny – Medyka railway corridor enabled a precise assessment of vertical and lateral wear progression in switch components. The diagnostic approach – based on laser profilometry and selected geometric track parameters – allowed for detailed, location-specific analysis.

The following key conclusions can be drawn:

a) Passenger traffic with a low volume of freight movement does not significantly reduce the technical functionality of the turnout. Forecasts based on observed degradation trends indicate that the service life of the system remains within a range of 30 to 50 years under current traffic conditions.

b) Vertical and lateral wear of rail heads stabilizes around 0.2 mm in the early operational period. This behavior is consistent across stock rail and switch rail with different radii and reflects predictable friction and contact-fatigue behavior.

c) Lateral inclination angles of the switch rail of around 20° are within safety thresholds defined by infrastructure standards, and do not currently require preventive intervention.

d) A local increase in vertical wear was observed in the vicinity of the first locking device. This may be attributable to limited accessibility for tamping and maintenance in that section, which highlights the influence of maintenance logistics on localized wear behavior.
e) The test results demonstrate a clear correlation between wear progression and cumulative axle loads passing through the turnout. This supports the potential for predictive maintenance models calibrated using tonnage data and geometry-specific diagnostics.
f) The repeatability of cross-sectional measurements along the switch rail length provides a strong foundation for time-based comparative analyses. These can be used to monitor subtle shifts in degradation rate and identify early indicators of abnormal wear patterns.
g) The observed physical wear is consistent with material flow phenomena and surface frictional effects, rather than structural defects. This suggests that grinding traces – although visible – do not represent fatigue-related damage but rather surface thermal effects without long-term impact on safety.
h) The methodology and field approach used in this study demonstrate practical applicability for long-term monitoring schemes. They are compatible with implementation in other sections of the national railway network, both in conventional and high-speed settings.

This comprehensive evaluation confirms that with proper measurement tools and standardized field procedures, reliable conclusions regarding infrastructure wear can be achieved. The study also demonstrates that turnout-specific geometry and traffic patterns must be jointly considered to plan maintenance actions based on data, rather than routine inspection cycles.

The predictive model proposed in this study is designed to estimate vertical and lateral wear progression in switch rails based on measurable operational variables. The input dataset includes laser profilometer readings (wear profiles at 200 mm intervals), cumulative axle load (tonnage), direction of traffic (entry or exit side of the switch), and local maintenance constraints (e.g., tamping accessibility).

The model development was based on multiple regression analysis, where wear depth is treated as a dependent variable, and the above factors act as independent predictors. The initial modeling utilized polynomial regression (second order) due to the nonlinear nature of wear accumulation over distance. Additionally, the method allows for the inclusion of site-specific parameters such as rail inclination angles (RPIA), blade geometry variations, and environmental conditions.

In future work, the regression approach may be extended to machine learning algorithms (e.g., decision trees, support vector regression) to improve robustness across variable track geometries. The predictive model is designed to identify high-risk zones along the turnout and optimize the timing of corrective maintenance interventions.

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