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Long-Term Settlement Behaviour of Turnouts with Different Sleeper Types in Austria

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Abstract

Turnouts, or switches and crossings, are critical components of railway networks, yet they experience concentrated dynamic loads that accelerate wear and drive high maintenance costs, particularly for ballast-related interventions. This study investigates long-term settlement behaviour across over 450 Austrian turnouts spanning approximately 20 years, considering wooden, conventional concrete, and concrete sleepers with under-sleeper pads (USPs). Longitudinal level (D1) measurements from standard track-recording vehicles were processed using an automated workflow to ensure temporal and spatial consistency, and a cumulative track geometry index (cTGI) was applied to quantify settlements. Settlement rates were corrected for traffic loading effects to enable robust comparison among sleeper types. Results indicate clear differences: conventional concrete sleepers exhibit moderate initial settlements but increasingly high rates with age, often necessitating early renewal; wooden sleepers show high initial settlements that decrease over time, allowing service up to 35–40 years; concrete sleepers with USP demonstrate consistently low settlements across all observed age groups, reflecting improved elasticity and ballast protection. These findings provide valuable input for turnout design optimisation, maintenance planning, and simulation studies, highlighting the long-term benefits of elastic support elements in mitigating track degradation and reducing lifecycle costs.

Keywords: turnouts, railway track settlement, long-term monitoring, track geometry, descriptive modelling, data analytics.

1 Introduction

Turnouts, also referred to as switches and crossings (S&C), constitute a crucial component of railway infrastructure. They enable trains to move between different tracks while in operation, providing both flexibility and resilience in network operations. The importance of turnouts is reflected in their extensive presence: the EU-27 railway system is estimated to include around 300,000 turnouts, which corresponds to roughly one turnout per kilometre of track [1]. Due to their complex design and the high, concentrated dynamic loads they experience, turnouts are especially susceptible to accelerated wear and degradation [2]. Consequently, they generate a disproportionately large share of investment and maintenance costs, accounting for up to one-third of annual track maintenance expenditures on some networks [3].

Maintenance of turnouts is a multifaceted process, involving a range of activities related to signalling components, switching mechanisms, and the track structure itself. Within the scope of track maintenance, the most cost-intensive tasks are associated with the ballast bed, including levelling, lining, tamping, and ballast cleaning [4]. The volume of ballast-related maintenance required also serves as an indicator of the turnout's achievable service life. Excessive demands for ballast interventions are economically undesirable, and component strategies should aim to minimise these requirements. The demand for ballast-related maintenance is most effectively represented by track settlement rates. Track settlements in railways are generally classified as either "absolute" (uniform settlement) or "relative" (differential settlement) [5]. For maintenance planning, the focus is on relative settlements, as differential track geometry significantly affects train dynamics.

One key design factor affecting turnout settlement behaviour is the sleeper type. Turnouts are available with a variety of sleepers, including wooden, conventional concrete, concrete with under-sleeper pads (USP), as well as steel and composite options. In-field or laboratory tests [6] and simulation studies [7][8] have revealed substantial differences in settlement behaviour across these sleeper types. However, such studies face two major limitations: 1) the sample size of compared turnouts is small, and 2) the observation period is relatively short. To overcome these limitations, we propose an additional approach that analyses settlements across a large number of turnouts over an extended time span. Descriptive modelling offers a suitable framework to meet these requirements.

Descriptive models allow for an objective analysis of settlement behaviour across a large number of turnouts. To ensure their reliability, several prerequisites must be met: consistent time-series data describing asset performance, coverage of a large number of turnouts with diverse designs, meaningful quality indicators accurately reflecting track settlement, and documentation of all maintenance interventions. Automated data preparation tools are also necessary to manage the substantial data volume, and appropriate statistical methods must be applied. The dataset available to the authors, obtained through long-term collaboration with the Austrian infrastructure manager ÖBB-Infrastruktur AG, fulfils these requirements. Recent research has further addressed challenges associated with large-scale data handling [9][10].

The aim of this study is to advance understanding of long-term turnout settlements by analysing wooden, conventional concrete, and concrete sleepers with USP using network-wide longitudinal level data spanning approximately 20 years. In total, settlement behaviour for over 450 turnouts was analysed, and a descriptive model was developed based on this extensive dataset.

2 Methods

In Austria, standard track-recording vehicles equipped with uniform track-geometry measurement systems have been deployed on main lines since 2001, carrying out measurements between two and six times per year. Among the recorded parameters, longitudinal level D1—defined in detail in the European standard EN 13848—represents one of the most relevant indicators. Longitudinal level is a standardised measurement signal, typically divided into the following wavelength ranges: D0 (0.6–3 m), D1 (3–25 m), D2 (25–70 m), and D3 (70–150 m). These wavelength ranges can be interpreted as a moving reference system, enabling track geometry assessment from a moving vehicle without the need for fixed trackside reference points. While D0 and D3 are partially optional, D1 and D2 are mandatory for infrastructure managers in Europe. Among these, the D1 longitudinal level is the primary input for planning ballast-related maintenance. Consequently, D1 is a suitable input variable for calculating track settlements which have the greatest impact on turnout maintenance.

Although these measurement systems are not explicitly designed for turnout inspection, data acquisition remains active while traversing turnout areas, allowing a substantial portion of the recorded data to be utilised. This applies exclusively to the measured branch of the turnout, which, in the majority of cases, corresponds to the main through-running track. For the aim of this study, we analysed the settlement behaviour of over 400 turnouts of the Austrian network. While some of the turnouts were selected for a specific purpose, the core of the data sample was defined randomly. By selecting turnouts with the internal numbers 1 and 2, we insured to include turnouts from through-going tracks in main lines in the sample. There is considerable variation in the turnout specifications in several aspects: we focused on different turnout designs, including straight and curved turnouts with various branch radii, sleeper types, loadings, allowed speed levels, turnout ages and different main driving direction.

Figure 1 presents four examples of longitudinal level measurements within a turnout zone. To ensure spatial and temporal consistency, an extensive data-alignment procedure as described in [9] was applied. Such an automated data-preparation workflow constitutes a fundamental prerequisite for the development of holistic statistical models of this type.

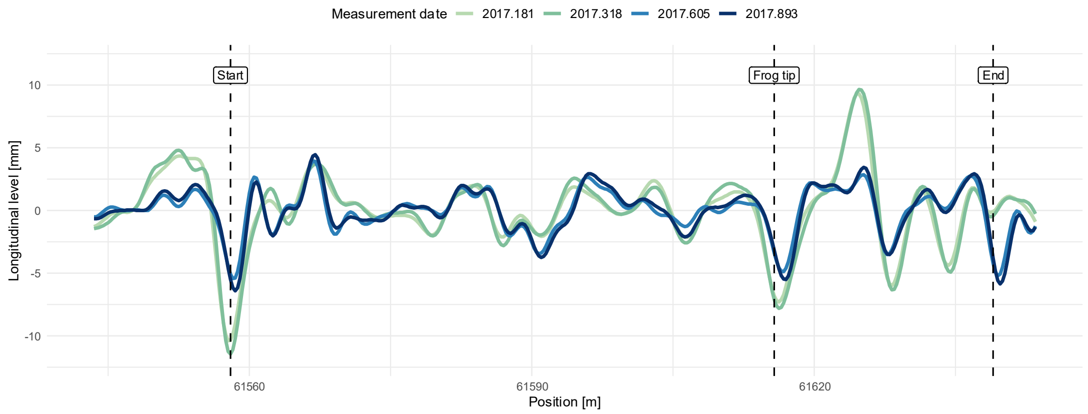

Figure 1: Four longitudinal level measurements in the turnout area

Vertical lines in Figure 1 denote the turnout location, marking the turnout start, the frog tip, and the turnout end. Typical temporal track behaviour can be identified through an analysis of the signal characteristics. As a result of progressive settlements, compared to the first measurement run (2017.181) the signal peaks are slightly more pronounced in the second measurement run (2017.318). Subsequently, a tamping intervention significantly improved the track geometry within the turnout, which is reflected in the third measurement run (2017.605) by an overall higher track quality. Thereafter, a renewed degradation of the track geometry can be observed in the final run (2017.893).

A more detailed examination of the signal characteristics indicates localised settlements—representing isolated track geometry defects—at the turnout start, at the frog position, and in the section between the frog and the turnout end. The latter corresponds to the transition zone between the final last sleeper and the first short sleeper, which is, together with turnout start and frog position, a well-known critical location for track geometry deterioration.

While raw measurement data provide valuable insight into the condition of individual turnouts and support the planning of targeted maintenance measures, the development of a descriptive model requires an assessment based on quality indicators. In open track, two longitudinal-level quality indicators are predominantly applied for this purpose. The maximum zero deviation of the raw signal represents a safety-critical, standardised metric and initiates spot tamping when the defined intervention limit is exceeded. In parallel, the standard deviation of the longitudinal level, calculated over a 100 m window, forms the basis for planning line tamping measures. Although this indicator is not safety-critical, it contributes to preserving track condition and reducing life-cycle costs in the long term. As this indicator reflects long-term track behaviour, it is better aligned with the objectives of the present study. However, due to the limited longitudinal extent of turnouts and the mathematically constrained reduction of window lengths, an adaptation of the index calculation is required. Instead of the standard deviation, the cumulative track geometry index (cTGI) is employed to characterise the average track geometry quality of turnouts. Based on Figure 2, the following section outlines the index calculation procedure using the recorded signals introduced in the preceding chapter.

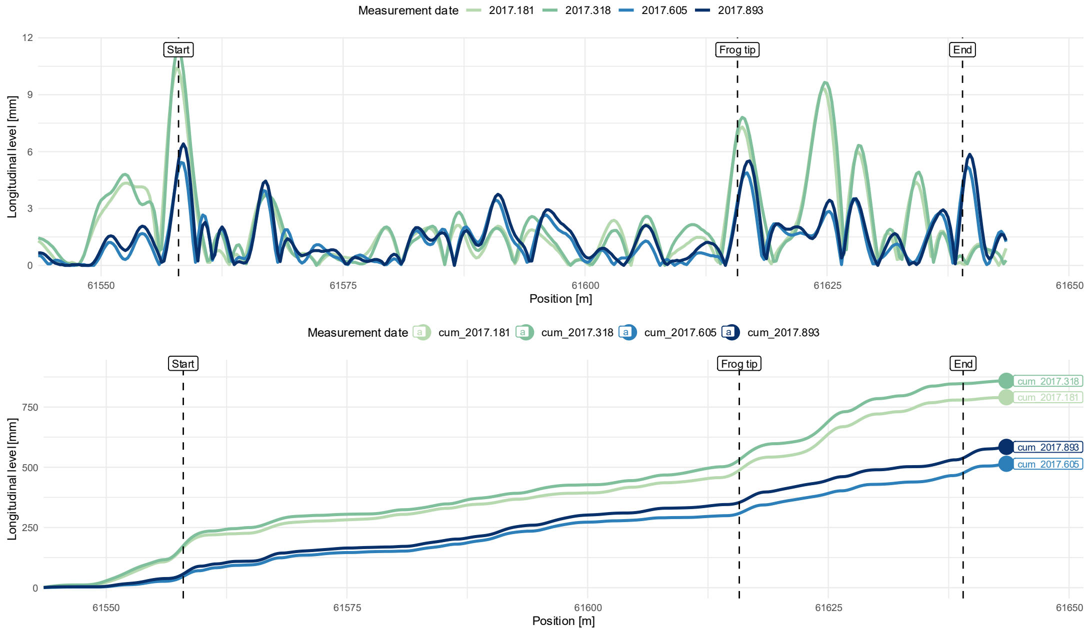

Figure 2: Calculation of the cumulative track geometry index based on four measurements, including RMS calculation and accumulation

In a first step, root mean square (RMS) values are derived from the longitudinal level signal by converting all negative signal components into positive values (upper part of Figure 2). This transformation affects neither signal amplitudes nor wavelengths. The resulting RMS values are then cumulatively summed along the longitudinal extent of the turnout. The coloured curves shown in the lower part of the figure represent these cumulative functions over the full turnout length. The terminal value of each cumulative curve, indicated by a marker, forms the basis for the calculation of the cTGI, with higher cumulative values corresponding to increased settlement levels.

The characteristic evolution of track settlement is again evident, with the index increasing from the first to the second measurement run, exhibiting a pronounced drop in the third run as a result of maintenance intervention, and subsequently increasing once more. In the final step of the calculation, the cumulative values are normalised by the number of data points used, which is equivalent to the turnout length. In contrast to the standard deviation, this normalisation renders the cumulative track geometry index independent of the evaluated turnout length and enables the assessment of turnout sections of limited extent. This feature is particularly advantageous when comparing turnouts of differing lengths, for example those with varying diverging radii. The representation of cTGI values over time provides a robust basis for time-series analysis and for investigating the temporal behaviour of turnout quality. Under normal operating conditions, progressive track settlement results in increasing cTGI values, whereas tamping interventions restore track geometry, which is manifested by an abrupt decrease in the index. Figure 3 exemplifies this characteristic settlement behaviour using data from one of the turnouts analysed.

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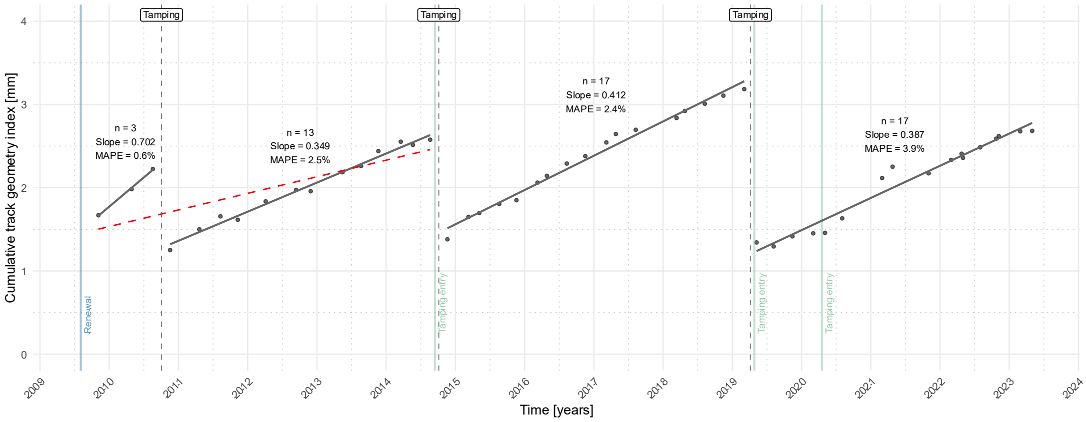

Figure 3: Time series analysis using the cumulative track geometry index

The time series begins with the renewal (installation) of the turnout in 2009. Each data point represents a cTGI value derived from an individual measurement run. The initial settlement branch extends until 2010, when stabilisation tamping was performed. Subsequently, three further settlement branches can be identified. The time series is segmented into deterioration branches by the execution of maintenance interventions. Maintenance information provided by the infrastructure manager is indicated by green vertical lines.

The maintenance entries for 2014 and 2019 appear to be accurate and are corroborated by the observed settlement behaviour. In contrast, an entry for 2011 is missing, while the entry recorded for 2020 does not correspond to a maintenance action that can be identified in the measurement data. Such inconsistencies are not isolated cases within the dataset analysed and have also been reported for other railway networks. Inaccurate localisation and missing documentation of maintenance activities represent a well-known challenge in railway research and must be addressed to ensure the development of reliable descriptive models. If not properly accounted for, settlement branches are incorrectly defined, resulting in biased settlement-rate estimates. This effect is illustrated by the additional dashed regression line between 2009.5 and 2014.75, which fails to represent the actual settlement trend.

Owing to the limited reliability of documented maintenance records, a maintenance-detection algorithm based on signal characteristics has been implemented. A detailed description of this algorithm is provided in the open-access publication by [10]. Once maintenance-free time intervals have been identified, settlement behaviour can be evaluated within these windows. For this purpose, linear regression models are applied and the slope of each regression is calculated. This approach is both feasible and effective. Steep settlement rates with high slope values indicate rapid track degradation and, consequently, poor turnout performance.

In the example presented, settlement rates are relatively high, with a particularly pronounced value of 0.7 mm/year observed for the initial branch. Elevated settlement immediately following turnout renewal is a well-established phenomenon associated with initial consolidation and explains the necessity of stabilisation tamping shortly after installation. The subsequent branches exhibit settlement rates of approximately 0.4 mm/year, which still indicate comparatively high settlement activity.

Since major data quality issues have been addressed during the upstream data-alignment process, the majority of settlement branches display stable, approximately linear growth. In cases where settlement behaviour cannot be adequately represented by a linear model—either due to residual data issues or genuine behavioural anomalies—an additional validation step is applied. For a settlement rate to be considered valid, the corresponding regression must include at least three data points, exhibit a positive slope, and yield a mean absolute percentage error (MAPE) below 10 %. Under these conditions, the derived settlement rates provide a reliable indicator of the quality of the respective settlement branch.

In the final step of the data-preparation workflow, the calculated rates are linked to the asset information of the analysed turnouts. This integration enables comprehensive statistical analyses and facilitates the comparison of turnout performance across different sleeper types over time. However, due to the distinctive statistical properties of the dataset, a careful and well-founded evaluation approach is required considering main performance driver which may dilute comparisons. Traffic type and volume represent well-established influencing factors on track settlement behaviour. Although more sophisticated modelling approaches incorporating both cumulative tonnage and vehicle-specific characteristics have been proposed, the inherent complexity of the subject has led most track-related studies to focus primarily on daily tonnage as the governing load parameter. As alternative approaches are not readily transferable and lie beyond the scope of the present work, daily tonnage is likewise adopted to represent the loading conditions of the turnouts analysed.

Figure 4: Statistical correction for the influence of daily tonnage on settlement rates

The left-hand side of Figure 4 shows the settlement rates of all turnouts considered, plotted as a function of daily tonnage, thereby illustrating its influence. Correlation functions are applied to quantify the relationship between daily tonnage and settlement rate. Given that sleeper type can substantially affect turnout behaviour, correlations are evaluated for the complete dataset as well as for three subsets corresponding to the respective sleeper types. Across all regressions, a clear and statistically significant (except concrete USP influence of daily tonnage on settlement rates) is observed. Increasing daily tonnage is consistently associated with higher mean track settlements. To isolate other influencing factors, the settlement rates are subsequently normalised using the derived correlation functions, thereby eliminating the effect of daily tonnage.

The pronounced differences between sleeper types are addressed by applying the scaling procedure separately for each category. The regression models described above are used to estimate expected settlement rates for each observed level of daily tonnage. By dividing these predicted values by their respective mean, scaling factors close to unity are obtained. These scaling factors are subsequently applied to compensate for and effectively remove the influence of daily tonnage from the calculated settlement rates.

$$\hat{b}_i = \beta_0 + \beta_1 \times T_i \tag{1}$$

$$f_i = \frac{\hat{b}_i}{\frac{1}{n}\sum_{k=1}^{n} \hat{b}_i} \tag{2}$$

$$b_i^{scaled} = \frac{b_i}{f_i} \tag{3}$$

$\hat{b}_i$ Settlement rates predicted by tonnage
β_0, β_1 Estimation factors
T_i Daily tonnage
f_i Scaling factors
b_i^{scaled} Scaled mean settlement rates

The scaled settlement rates as a function of daily tonnage are presented on the right-hand side of Figure 4, where no statistically significant relationship can be identified. Although the scaling procedure was applied separately for each sleeper type, the resulting global regression exhibits no remaining correlation, thereby demonstrating the effectiveness of the normalisation approach. Moreover, as the scaling factors are close to unity, the overall magnitude of the mean settlement rates remains essentially unchanged, allowing direct comparison with non-scaled values. Consequently, long-term turnouts settlements for turnouts with different sleepers will be compared based on scaled mean settlement rates.

3 Results

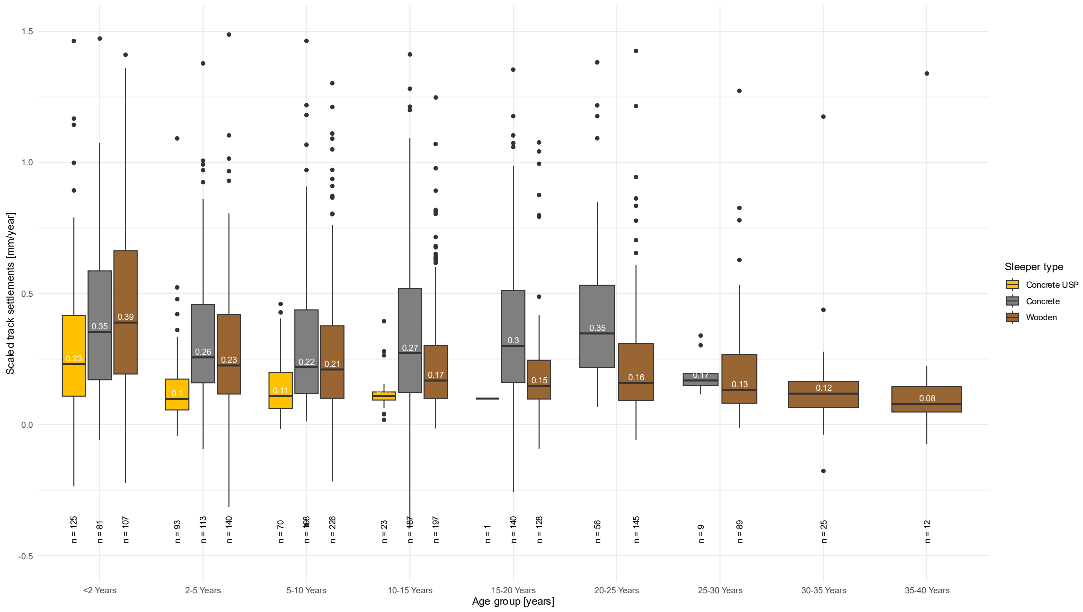

Figure 5: Settlement rates for different sleeper types and age groups

Conventional concrete sleepers exhibit the expected settlement behaviour: following relatively high initial settlements during the first years after installation, settlement rates decrease to a minimum in young turnouts and then increase steadily with age, reaching a maximum at approximately 20–25 years. Beyond this age, no concrete-sleeper turnouts are present in the dataset, indicating that renewals typically occur before this service life is reached. An exception is a small group of nine settlement branches aged 25–30 years; however, the limited sample size does not allow for statistically meaningful interpretation.

Turnouts equipped with wooden sleepers show a distinctly different behaviour. Although initial settlements are higher than for the other sleeper types, settlement rates decrease continuously over time. Some wooden-sleeper turnouts remain in service for 35–40 years, considerably longer than turnouts with concrete sleepers. Settlement rates near the end of the service life are approximately five times lower than directly after installation and remain lower by a factor of about 2.8 compared with the stable condition observed in young wooden-sleeper turnouts.

Concrete sleepers with under-sleeper pads (USPs) generally exhibit the lowest settlement rates. Initial settlements are significantly lower than those of the other sleeper types (by factors of 1.7 and 1.5), and settlement stabilises rapidly after installation, resulting in consistently low settlement rates across all available age groups. As concrete USP sleeper turnouts have been in service for only about 15 years, no data are available for older age classes.

Table 1 compares settlement rates of turnouts with different sleeper types using age-group-specific factors, with the overall median settlement rate of 0.21 mm serving as a reference value. Although the median provides a useful benchmark, it does not represent a desirable or target settlement behaviour, as it is strongly influenced by the large proportion of mid-aged concrete-sleeper turnouts in the dataset and initial settlements.

Age	**<2**	**2-5**	**5-10**	**10-15**	**15-20**	**20-25**	**25-30**	**30-35**	**35-40**
Wooden	186%	110%	100%	81%	71%	76%	62%	57%	38%
Concrete	90%	113%	105%	159%	200%	219%	131%		
Concrete USP	66%	38%	50%	41%					

Table 1: Settlement values for different sleeper types and age groups relative to the median

A value of 100% corresponds to the median settlement rate. Settlement rates in Table 1 above the median are highlighted in red. Concrete sleepers equipped with under-sleeper pads (USPs) exhibit settlement rates below the median for all age categories up to 15 years, beyond which no data points are available. Turnouts with wooden sleepers show disproportionately high settlement rates during the first 5–10 years of service; thereafter, settlement rates become relatively low and even decline with increasing age. Conventional concrete sleepers display comparatively high settlement rates across all age categories, with particularly elevated values in the older age groups.

4 Conclusions and Contributions

It is possible to draw several conclusions from the results. A comparison of the sleeper types indicates a clear performance advantage of concrete sleeper with USP, followed by wooden sleeper. Conventional concrete sleeper has been found to demonstrate the poorest settlement behaviour. Due to the high mass of the track grid, concrete sleeper demonstrates adequate stability during the initial years of use. However, settlements become a significant concern after a certain period. Our approach to explanation is that the combination of inadequate elasticity between the bottom edge of concrete sleepers and the ballast bed, in conjunction with dynamic impact loads resulting from rail surface irregularities in turnouts (e.g. crossing, welds, insulated rail joints), leads to ballast breakage and abrasion. While the track can withstand this for a period of time, once a tipping point is reached, excessive ballast breakage and rearrangement can lead to significant settlements (up to 200% of the median settlement). When ballast is fouled, tamping becomes less effective, necessitating the early renewal of turnouts. This explains the missing data points in older age groups for concrete sleepers. The reduced (but still high) settlements in the 25-30 age group can be explained by the fact that only concrete sleeper turnouts with adequate functionality reach this age in the first place.

The situation is contrary for wooden sleeper. Due to the structure's reduced mass, the initial stability levels are not as high, which results in significant settlements during the initial years. However, due to the higher elasticity of the system, the ballast is less susceptible to damage compared to concrete sleeper. Once the track has settled into a stable position, stability is high and settlements tend to be low. Furthermore, since the ballast remains intact, tamping is an effective solution, even for older turnouts. As a result, the data sample includes turnouts from older age groups, which have not been renewed. This prompts an interesting question. Concrete sleeper benefits from higher durability than wooden sleeper due to its material decay resistance. However, based on the data analysed, this advantage cannot be used for turnouts. Due to the necessity of replacing turnouts with concrete sleepers as a result of a worn ballast bed, service lives are even shorter than those of turnouts with wooden sleepers. This effect is evident in the data, even though in Austria, ballast bed cleaning is carried out as required for turnouts with concrete sleepers.

The concept of the concrete sleeper with USP is to combine the benefits of concrete sleeper, such as high stability and durability, with those of wooden sleeper, including high elasticity and ballast protection. The effectiveness of this approach is evident from the low settlement rates observed in the initial years and in mid-aged groups. As USP has been used for turnouts in Austria for approximately 15 years, no data is available beyond this timeframe. It is anticipated that settlements will remain at a minimal level, a result of the ballast's protective function of the elastic pads. Furthermore, in open-track applications, even older concrete sleeper sections equipped with USPs can be analysed, demonstrating consistently low and stable settlement behaviour, particularly in higher age groups.

In addition to providing valuable input for component strategy development, these results may also serve as a reference for simulation studies. Based on a detailed analysis of more than 450 turnouts, it has been shown that long-term settlement behaviour differs significantly among the three sleeper types considered. This information can be used by simulation tools for validation purposes. Moreover, the anticipated magnitude of settlement represents an important input parameter for such simulations. The developed descriptive model also allows for more detailed referencing of settlement behaviour in specific turnout zones, such as the frog area and the transition zones at the front and rear of the turnout. These areas are particularly critical and represent key targets for optimisation through improved design solutions. Future research would benefit from closer cooperation between simulation-based approaches, as discussed in [11] and [12], and descriptive modelling approaches, such as those applied in this study, as well as more specialised models.

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References

[1] UIC—International Union of Railways, "Capacity for Rail FP7-SST-2013-RTD-1, Public Deliverable D 1.3.1, Operational Failure Modes of Switches and Crossings," Belgium, 2015.

[2] A. M. Remennikov and S. Kaewunruen, "A review of loading conditions for railway track structures due to train and track vertical interaction," Mar. 2008. doi: 10.1002/stc.227.

[3] C. Letot *et al.*, "A data driven degradation-based model for the maintenance of turnouts: A case study," in *IFAC-PapersOnLine*, Sep. 2015, pp. 958–963. doi: 10.1016/j.ifacol.2015.09.650.

[4] M. Fellinger, "Sustainable Asset Management for Turnouts - From measurement data analysis to behaviour and maintenance prediction," no. August, pp. 1–157, 2020.

[5] I. Grossoni, W. Powrie, A. Zervos, Y. Bezin, and L. Le Pen, "Modelling railway ballasted track settlement in vehicle-track interaction analysis," *Transportation Geotechnics*, vol. 26, Jan. 2021, doi: 10.1016/j.trgeo.2020.100433.

[6] G. Grohs, P. Pircher, M. Quirchmair, H. Loy, K. Six, and F. Pospischil, "Behavior of turnout sleepers in a large-scale ballast box test," *Sci. Rep.*, vol. 15, no. 1, Dec. 2025, doi: 10.1038/s41598-025-01751-3.

[7] S. Kaewunruen, T. Ishida, and A. M. Remennikov, "Dynamic performance of concrete turnout bearers and sleepers in railway switches and crossings," *Adv. Civ. Eng. Mater.*, vol. 7, no. 3, May 2018, doi: 10.1520/ACEM20170103.

[8] A. Manalo, T. Aravinthan, W. Karunasena, and N. Stevens, "Analysis of a typical railway turnout sleeper system using grillage beam analogy," *Finite Elements in Analysis and Design*, vol. 48, no. 1, pp. 1376–1391, Jan. 2012, doi: 10.1016/j.finel.2011.08.007.

[9] J. Egger, M. Loidolt, S. Marschnig, and S. Offenbacher, "Automating Signal Synchronization for Enhanced Track Monitoring in Turnouts," *Applied Sciences*, vol. 16, no. 1, p. 223, Dec. 2025, doi: 10.3390/app16010223.

[10] J. Schatzl, F. Gerhold, M. Loidolt, and S. Marschnig, “Enhancing Predictive Maintenance Through Detection of Unrecorded Track Work (Unpublished manuscript),” 2024.
[11] I. Grossoni, Y. Bezin, and S. Neves, “Optimisation of support stiffness at railway crossings,” *Vehicle System Dynamics*, vol. 56, no. 7, pp. 1072–1096, Jul. 2018, doi: 10.1080/00423114.2017.1404617.
[12] X. Li, J. C. O. Nielsen, and B. A. Pålsson, “Simulation of track settlement in railway turnouts,” *Vehicle System Dynamics*, vol. 52, no. sup1, pp. 421–439, May 2014, doi: 10.1080/00423114.2014.904905.