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A Risk-informed Framework for Maintenance Decision-making of Railways Over Bridges Under Seismic Influence

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This work presents a risk-informed framework to allow for the introduction of an external risk scenario resulting from the seismic influence of railways on supporting structures. Previous traditional performance-based railway asset management approaches often separate operational degradation from external hazard effects, which limits efficient decision-making regarding appropriate maintenance strategies. The framework considered the probabilities of seismic events occurring on a selected bridge and their translated impact on the railway track. The proposed framework integrates the effects of seismic influence on the baseline asset degradation trajectory, obtained using a continuous-time Markov deterioration process. The hazard component is modelled using a Poisson distribution for earthquake occurrence frequency, coupled with a truncated normal distribution of magnitudes to estimate the likelihood of different seismic intensities. Afterwards, fragility curves were obtained to assess the occurring probabilities of exceeding damage states. By performing a static non-linear analysis on the bridge, the spectral displacements of each damage state were translated into deterioration rate multipliers, producing updated deterioration curves. Further, the expected risk for the railway line is computed as the product of the probability of each damage state and its corresponding consequence, expressed in terms of repair cost, downtime or functional loss, based on available data and the preference of the asset manager. This framework provides a quantitative basis for comparing maintenance interventions. Improvement assumptions are made for preventive, corrective and replacement maintenance strategies to evaluate their efficiency in limiting the expected risk. The results justified how introducing hazard-based assessment can significantly alter baseline trajectories and associated risk profiles, highlighting the importance of linking structural fragility to long-term performance models. The framework improves decision-making for asset managers by integrating a hazard-based risk assessment into the deterioration model and will contribute to providing asset managers with a more efficient tool for planning interventions on railway bridges.

Keywords: Key Performance indicators (KPIs), Asset management, Risk-informed Decision-making, Railway performance, Bridge safety and Durability.

1. Introduction

The economic reliance on railways in Europe is continuously on an increasing trend, backed by recently recorded data. Passenger usage data alone for this critical infrastructure between 2022 and 2023 shows an 11% increase, accounting for about 429 billion passenger-kilometers (Eurostat 2024). As growth is expected, complex railway infrastructure systems must be adequately resilient, sustainable, smart, affordable, and reliable. In light of this, the European Green Deal and the European Union’s sustainability and smart mobility strategy considers new objectives to enable an environmentally friendly and efficient trans-European network. Evidently, this plan will require thorough assessments and mitigation of the infrastructure's total lifecycle cost.

In the In2Track2 research project (Morais, M. J. et al. 2021), a maintenance framework was developed to address recent limitations in railway maintenance decision-making. These recent limitations, highlighted in (Lyngby et al. 2008; Strauss et al. 2016) have necessitated a risk-based approach to intervention planning. This study will focus on using the track geometric limits obtained in the In2Track2 research project to predict the performance of a railway over a bridge and how bridge responses to seismic activity can affect performance predictions and future maintenance strategies.

The widely reported impact of seismic events on railway according to (Lai et al. 2020) results in structural damage to rails, bridges, and train stations, among others, compromising safety and leading to several consequences. Studies such as (Wei et al. 2024; Fernandes et al. 2022), on railway bridges and other supporting structures tend to place greater emphasis on the seismic resilience of the supporting structures, without considering the bearing on the railway track. There is still a need for more detailed research on how the dynamic responses of bridges affect the prediction of railway deterioration for maintenance strategies. With a fully connected track over a bridge, it is highly likely that external shocks to the bridge could affect the track's characteristics and according to (Shaohui et al. 2025), the operational capacity of a railway track after a seismic event is fundamental to post-seismic rescue efforts.

2. Framework Overview

The framework developed applies to the maintenance decision-making stage after forecasting the track degradation over time using the Markov Continuous chain. The framework considers the normal operational baseline degradation of the railway track and how the mean degradation trajectory changes in the event of an earthquake. The flow diagram in Fig. 1, highlights the various steps of the framework, starting from the event scenario and hazard assessment to the hazard effects and consequences stage, adapted from (Morais, M. J. et al. 2021; Eidsvig et al. 2021).

2.1. *Baseline deterioration model*

The Markov predictive model was selected for this framework's development, considering the nature of the available data for the case study. The Markov model is suitable for predicting accumulated degradation for many engineering structures, such as rails and bridge infrastructures. It is efficient in situations where state transition probabilities mirrors the interaction between the track degradation and random factors (Liao et al. 2022).

2.2.1. *Seismic Hazard and Fragility Modelling*

Event Scenario & Hazard Assessment:
The seismic event, which consequences may be differentiated by a damage level (i.e. minor, moderate, severe, or total collapse of the structure), is assessed and categorized based on data from a specific location. Therefore, classification of the event depends heavily on the magnitude and nature of the seismic activity. Data acquisition for intensity thresholds was based on historical records, reliable expert opinion, and research studies referenced in the case study, section 3.2.

Exposure of Asset & Hazard Effects:
Research from (Eidsvig et al. 2021), stipulates that the development of vulnerability models can be done using expert judgment, empirical approach based on observations, the Analytical approach based on analytical or numerical solution methods and a combination of two or all three of the above approaches. In this study, the intensities of the considered events determined the effects on the deterioration rates using the inelastic displacements until collapse. The changes resulting from each damage category affected the baseline transition probabilities, generating the updated baseline curve on which new maintenance strategies are determined. Selected statistical formulas used in this section were derived in accordance with (Sheldon M. Ross 2010; Ross 2010; Bommer and Scherbaum 2008).

Hazard Distribution:
Based on the historical seismic occurrence, empirical simulations are made using a Poisson process. For a possible event an intensity is assigned for each damage state (minor, moderate, severe and collapse). This is sampled from a truncated normal distribution bounded by a maximum and minimum, based on the historical seismic data (see 3.2). The truncation

is applied using inverse transverse sampling to ensure the simulated event lies within the acceptable physical range.

<u>Hazard Fragility:</u>
Using the sampled earthquake magnitude, the probability of exceeding the defined damage states is calculated. These curves, called fragility curves, represent the likelihood of a damage state. A performance model is then developed based on the likelihood of each damage state occurring.

2.2.2. *Risk Quantification*

The expected Risk (R(t)) is quantified based on the updated baseline transition probabilities and the expected consequences vector for each condition state. The risk quantification equation within the service life of the track is presented in Eq. (1), (Eidsvig et al. 2021) . This could take the form of repair costs, downtime, and safety losses, among others. For this study, an assumed repair cost for each transition state was used.

$$\mathrm{R(t)} = \sum_{i} \mathrm{P_i(t)} C_\mathrm{i} \tag{1}$$

where;
$P_i(t)$= probability of being in state *i* at time *t*,
C_i= consequence (cost, downtime, safety loss, amongst others) associated with that state

The state probabilities are determined using a linear approximation of the mean condition index to provide consistency in the predicted trajectories. Seismic effects are introduced by modifying the deterioration process with new hazard-dependent rate multipliers, combined with discrete improvements from maintenance actions. The computed expected risk over the service life is discounted to "prevent value" to evaluate the schedule effectiveness and cost-efficiency.

3. Case Study

The case study used to test this framework was adapted from (Morais, M. J. et al. 2021), which examined an existing railway line in Portugal. For the purpose of this study, data on geometric performance indicators (longitudinal levelling and alignment) were used to develop the baseline degradation curve. The railway track under consideration is divided into three individual zones (A, B, C) spanning 194.6, 266, and 11.4 km, respectively. Fig. *2* depicts the nature of the data obtained for the railway track.

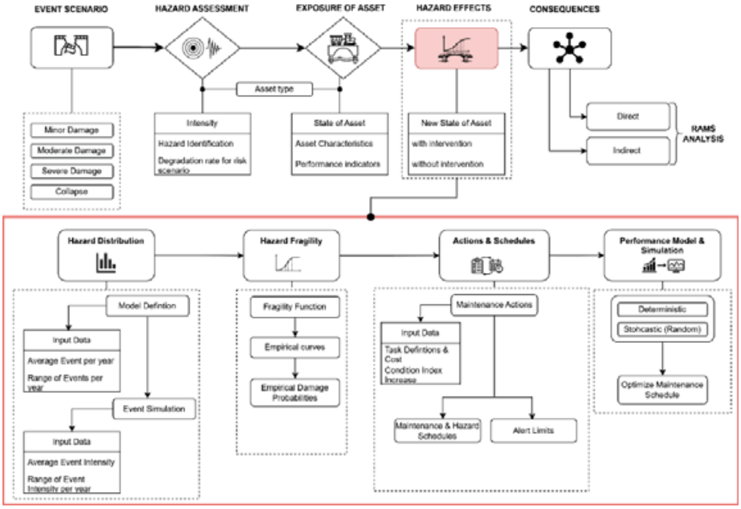

Fig. 1 Risk-based decision-making framework, (Ampofo 2025).

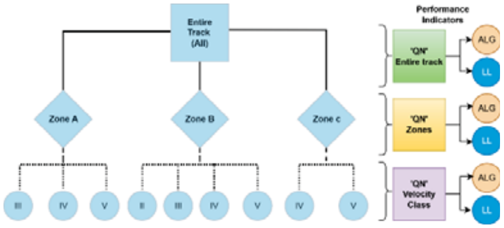

Fig. 2 Data distribution for case study (Ampofo 2025).

3.1. *Predicted Asset Condition over time (Baseline Curve) – Entire track*

According to EN 14363 the railway track is considered to have three discrete quality levels (QN1 to QN3). By adopting the continuous Markov chain predictive model, the transition rate and probability matrix are estimated from the track data presented in Table 1. Using these values, a baseline curve is developed as shown in Fig. 3. indicating a gradual asset degradation over 40-year service life period. A steady transition is observed over the 40-year period towards a declining state, capturing the gradual increase in transition probabilities from state 1 → 2 → 3.

3.2. *Seismic Influence on Deterioration*

Establishing the relation between the railway track and a supporting structure, an assumption is made considering a railway track over a selected bridge. To define the seismic parameters and event distribution, historical data and expert opinion were used for this study. Damage categories and thresholds were selected in line with data recommendations from (Anbazhagan Panjamani and Nassir Alarifi 2017; Bruce A. Bolt). Additionally, historical seismic data for Portugal were obtained from (Earthquakelist.Org 2025). Due to the strong correlation between railway infrastructure accidents and earthquake magnitude ≥ M4 provided in (Maneerat and Rungskunroch 2024), earthquake data considered were ≥ M4. To estimate the probabilities of the various damage states presented in Table 2, expert opinion, the magnitude threshold for each type of damage state, and historical data on the observed magnitudes were considered. From the historical data obtained from (Earthquakelist.Org 2025), the earthquake magnitudes selected for the various damage states were: (i) Minor damage: M4, (ii) Moderate damage: M5, (iii) Severe damage: M6, (iv) Collapse: M7. From the acquired data, the following assumptions was used for the empirical simulations. (i) Average Intensity: 4, (ii) Maximum Intensity: 8, (iii) Minimum intensity: 2

3.2.2. *Non-Linear Static Analysis*

An objective of this research is to use the developed framework to evaluate the effects of failures due to an external shock for supporting structures. These resulting changes, if not considered, could lead to economic consequences in the management of the track. In performing a static non-linear analysis on a selected bridge, an assessment of the inelastic deformation is done. Inelastic deformation beyond the yield point of a given bridge permanently affects the structure's behaviour. The static nonlinear analysis assesses the displacement thresholds for each damage state of the selected bridge to evaluate its seismic vulnerability. The ratio of damage-level displacement to the total inelastic displacement is evaluated and applied as a multiplication factor to the baseline transition rates. A simple bridge model of length 50.6m, supported by two columns, is considered for analysis, using Diana 10.9 software. Results from the first mode shape is presented in Fig. 4.

Table 1 Transition rate and matrix for the entire railway track.

Section	Transition Rate (θ)	Transition Matrix (P)
All track	[0.079 0.203]	[0.912 0.079 0.009] [0 0.805 0.195] [0 0 1]

Table 2. Probability of occurrence for each damage state.

Damage State	Probability
No Damage	0.140201
Minor Damage	0.674555
Moderate Damage	0.155116
Severe Damage	0.028040
Collapse	0.001690

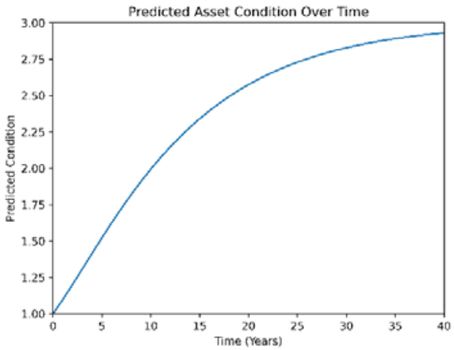

Fig. 3. Baseline Degradation Curve

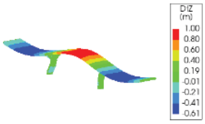

Fig. 4 Mode shape 1, with Eigen Frequency: 4.789

The pushover curve depicted in Fig. 5 is obtained from data in the vertical (Z) direction. It depicts an elastic response towards the yield displacement of approximately 0.02m, showing declining stiffness. The transition to the inelastic deformation is observed beyond the yield point as the damage intensifies and accumulates. The peak shear force for the selected model is recorded to be around 27500 kN with an ultimate displacement (Du) of 0.15m. This ultimate spectral displacement corresponds to the model's ultimate strength capacity. Observed at the tail end of the curve is a gradual drop in peak force signalling the onset of global damage. Using the log-normal distribution hypothesis adopted in Lagomarsino et al (2003) and cited in (J.M. Bairán and García 2023; Lagomarsino and Giovinazzi 2006),

Estimating New Transition rates

The new transition rate for the updated baseline degradation curve is estimated using Eq. (2-3) and presented in Table 3. From these new data, baseline curves are generated to represent the effect of each damage state on the track degradation (see Fig. 6).

$$\Delta_{DS} = \frac{\boldsymbol{S_d}}{\boldsymbol{S_T}} \tag{2}$$

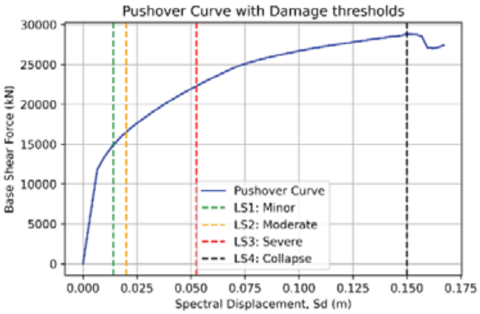

Fig. 5 Pushover curves with damage thresholds

Where, $\boldsymbol{S_d}$ is the spectral displacement for the damage state and $\boldsymbol{S_T}$ is the total spectral displacement

$$\boldsymbol{\theta_{ND}} = \boldsymbol{\theta_B x}(\boldsymbol{1} + \Delta_{DS}) \tag{3}$$

Where;
θ_{ND} is the new transition rate for the damage states.
θ_B is the baseline transition rate.
Δ_{DS} is the damage state deterioration factor expressed as a percentage.

Table 3 New transition rates based on damage states

Damage State	Deteriorating factor (Δ_{DS})	New Transition rates (θ_{ND})
Minor Damage	0.09	[0.085 0.221]
Moderate Damage	0.13	[0.089 0.229]
Severe Damage	0.33	[0.105 0.270]
Previous Baseline transition rate:		[0.079 0.203]

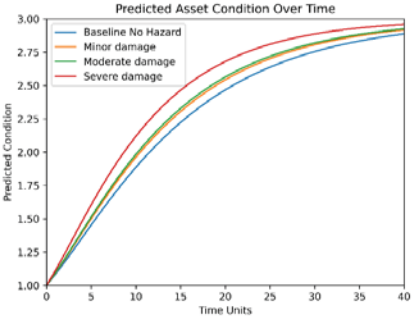

Fig. 6 New baseline curve for each damage state against baseline without seismic event

3.2.3. *Maintenance strategy assessment*

Three maintenance schedules in line with EN 13306:2017 (Sedghi et al. 2021; Sharma et al. 2018) are proposed for the performance model to improve the asset condition at stipulated to periods (for predictive maintenance, corrective maintenance, and total replacement of the asset) represented in Table 4. The estimated occurring probabilities of the seismic event, together with the updated transition rates, are used to determine the new asset baseline deterioration over the 40-year service life of the asset. Using these maintenance strategies and the new transition rates, the performance model simulates the performance of the asset considering the external event. Based on this performance model, the expected risk for each curve and maintenance strategy is plotted to identify the less risky maintenance strategy. The assumptions made for the repair consequences of the risk quantification process of each asset transition state (CI-1 to CI-3) were €0, €20,000, €50,000 respectively.

Table 4. Maintenance schedules

Schedule No.	Type	Interval
1	Preventive	Every 5 years
2	Corrective	Every 10 years
3	Replacement	Every 20 years

3.2.4. *Asset Performance*

The results from the asset performance in Fig. 7 shows two baseline deterioration curves: one with seismic effects and one without. The two curves clearly show the seismic-influenced baseline curve with a much steeper deterioration curve than the normal, regular operation baseline curve, using the new formulation. Additionally, maintenance strategies applied to the updated baseline trajectory indicate that consistent corrective maintenance every 10 years (schedule 2) will perform much better in the system than the other schedules considering the seismic scenario. Risk quantification for all trajectories shown in Fig. 8 is performed to determine the expected risk for each curve. The lifecycle risk distributions were presented using probability density histograms to compare the different maintenance strategies.

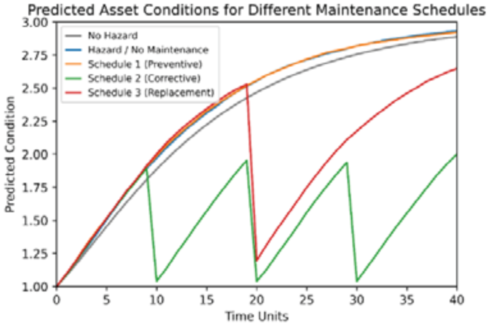

Fig. 7 Results from performance simulations considering randomly occurring seismic activities

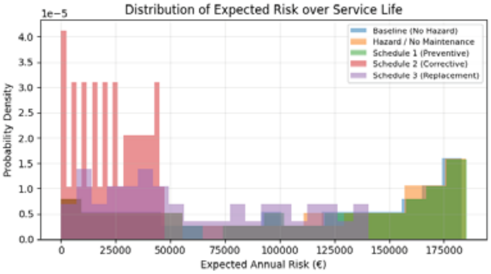

Fig. 8 Expected risk of deterioration trajectories and maintenance schedules

4. Discussion

The results of the case study indicated a realistic deterioration curve for the railway track following a seismic event. This indirectly affects the maintenance strategy, since the occurrence of a seismic event changes the baseline degradation observed in this study. In this analysis, the new baseline deterioration curve, based on the observed probabilities of the expected hazard, was nearer to the actual baseline deterioration. This occurred mainly due to the minor seismic activity being more likely to occur. In the empirical analysis of seismic activity, minor-damage earthquakes increases the deterioration rate by merely 9%. From these results, it can be inferred that the appropriate maintenance scenario will remain unchanged, considering both degradation curves. However, in a different location prone to higher seismic intensities, the new baseline deterioration will progress much faster than the obtained output indicates. This may result in different outcomes when comparing maintenance strategies, for example different maintenance application periods. The lifecycle risk distribution for each trajectory matches the expected risk satisfactorily. As indicated in Fig. 8, the risk distribution show areas of concentration and the trajectory that has the highest expected risk. A brief economic assessment was conducted to determine the "present value" for each trajectory and the cost-benefit ratio for the various maintenance schedules. This quantitative analysis was done to provide a broader perspective on the application and the decision-making process for asset managers. For maintenance schedules 1-3, the following maintenance costs were randomly assumed: €20,000, €40,000, and €100,000, respectively with a 3% discount rate. For the three maintenance schedules the respective results for the risk-cost ratio (risk avoided per € spent) were: 0.41,23.04 and 15.34 respectively. Indicating that the maintenance schedule 2 has the lowest risk expectancy.

5. Conclusion

The study translates the inelastic behaviour of the bridge into factors that increase the transition state for the railway track as a function of spectral displacements. In the application of the framework, the hazard distribution, hazard effects, and bridge characteristics are the main contributing factors to the modified deterioration behaviour. The bridge responses and the nature of the seismic activities govern the spectral displacements needed to estimate the deterioration factors associated with the damage states. In the case study, the predominant seismic activity was within the minor damage threshold; hence, a very mild change in the degradation curve as a result of seismic effects as compared to the baseline degradation.

Estimating the expected risk for the baseline trajectories and the maintenance schedules required a pragmatic approach that considered the probability of each condition state and its consequences. Rounding up and interpolation for the three condition states per year. The computed expected risk confirmed that the baseline curve with seismic activity has the highest total expected risk. Again, from our performance model, a corrective maintenance program initiated every 10 years was shown to significantly reduce this expected risk, possibly prolonging the track's lifespan. Despite these results, the performance model inherently relied on several modelling assumptions. The cost of maintenance strategies, the cost of deterioration into a condition state, improvements to maintenance strategies, and the discount rate for present value estimation. Estimating the true value of these assumptions will be the true test in industrial applications and decision-supporting tools. Further research is required to determine the true values of these areas and improve the overall reliability of decision-making. For reliable updates of transition states, applying real-time monitoring of existing structures will ensure a much more robust dataset for hazard simulations and dynamic responses. Overall, the framework applied to the case study supports the premise of incorporating hazard-based structural performance into the railway deterioration model. This enhances risk awareness in maintenance planning. The final decision-making process for asset managers will require a thorough RAMS analysis on the selected maintenance strategies to examine all consequences.

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