Decision Support System for Ballast Maintenance in Railways

Hussain Ramahi

Master Thesis

DTU Electrical Engineering
Department of Electrical Engineering

Agenda

- Research problem, objectives and process
- Theoretical Framework
- Methodology
- Results and Conclusion

Research Background

Problem statement

- Worldwide railway traffic has been increasing remarkably over recent decades, and this is a result of significant investments in different facets of the railway sector and changes in the demographics of society. The railway traffic is expected to grow further as both passenger and cargo transportation is shifting from road to rail
- Infrastructure managers face an increase in demands by traffic operators and passengers and be required to ensure safe, reliable and comfortable railway
- Providing safe and reliable train transportation is a rather complicated task; for infrastructure owners, the ability to meet those requirements rely on the capability of evaluating the occurrence of geometry defects in the decision-making process supporting the maintenance and renewal service
- Evaluating track geometry conditions by capturing the numerous factors affect the degradation process is challenging, and the need for developing proper models that address the critical aspects of railway track geometry degradation becomes more urgent

Research Objectives and Questions

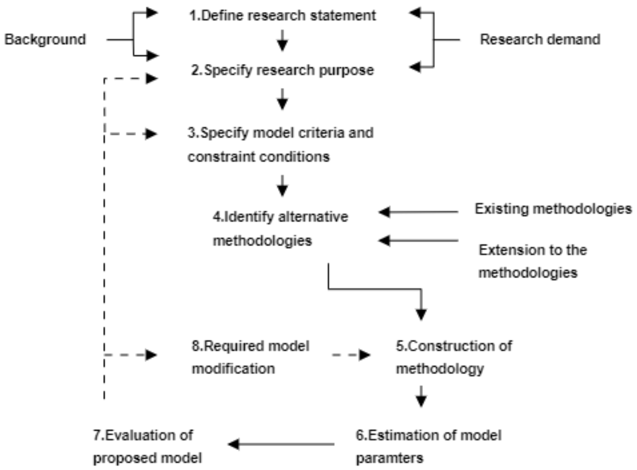
Research Objectives

- To develop an integrated degradation model that can simulate the degradation path of the longitudinal level for track geometry, by considering the degradation of subgrade, ballast settlement as dominant parameters subject to accumulated load.
- To propose a decision support tool for determining when to plan for preventive maintenance and track renewal, based on maintenance performance indicators generated from modeling the evolution of the track structure condition.

Research Questions

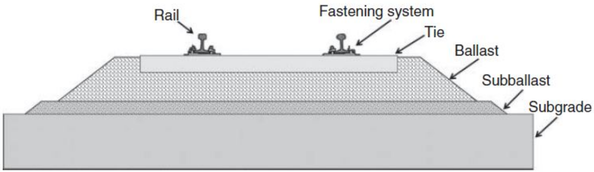
- How can the track geometry degradation be modeled, taking into the deterioration of track modulus and recovery effect of tamping?
- How do different maintenance intervention limits affect the track geometry condition and decision-making process?

Research Process



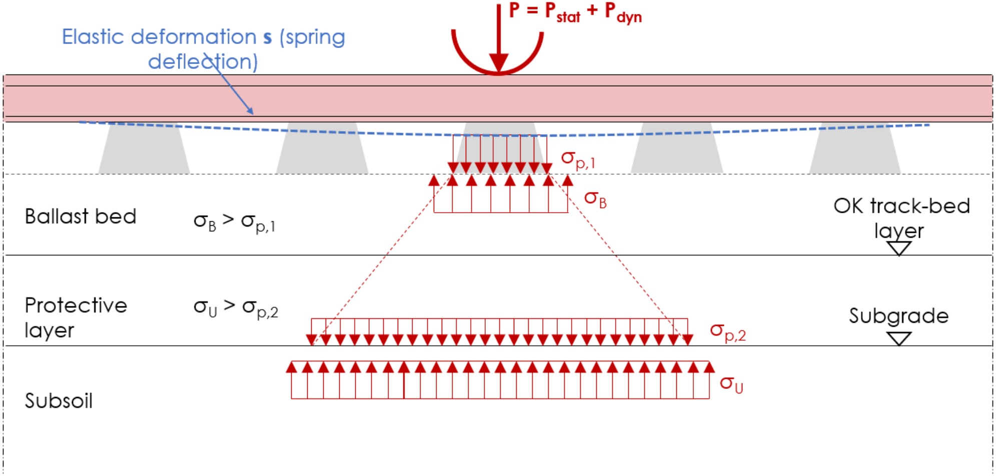
Track Structure and Geometry

Track Structure:



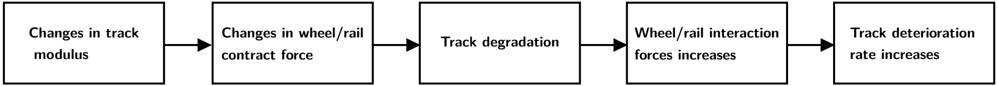
Track Geometry:

Load Distribution in Railway Track

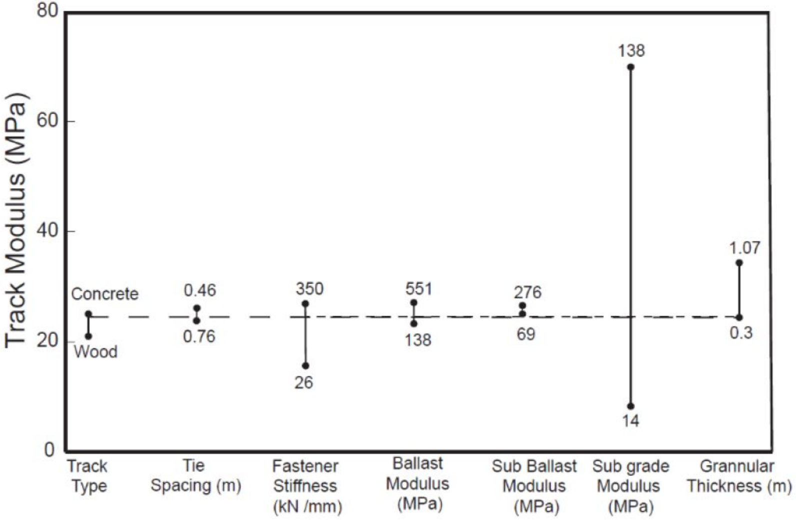


Track Geometry Degradation and Track Support Stiffness

- Track irregularities develop as a result of dynamic, static and semi-static contact forces produced by the wheel-rail interface.
- Dynamic track forces result in longitudinal loads that are parallel to the track and affect the degradation of track geometry and track stiffness.
- Track stiffness is a measure of vertical stiffness between the rail base and track foundation.
- Based on static and dynamic models, the conclusion is that the subgrade contributes to the most significant influence on the overall track responds.



Impact of track components on track modulus



Track Quality Index

Standard deviation of a signal over a track section:

$$SD = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \overline{x})^2}{N-1}}$$

Wavelengths:

- $D1: \ 3\ m \ < \lambda \leq 25\ m$
- $D2: \ 25\ m \ < \lambda \leq 70\ m$
- $D3: \ 70\ m \ < \lambda \leq 150\ m$

- Mean to peak value in the wavelength range 3 to 25 m.
- Standard deviation over a defined length, typically 200 m track section.
- Zero to peak value of (isolated defects) that exceed threshold.

Maintenance Limits

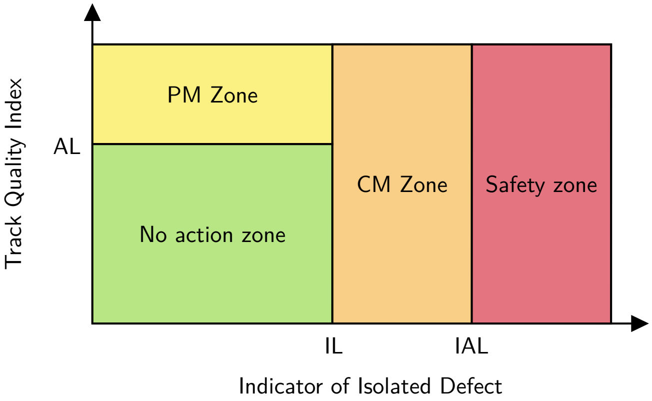


Figure: Maintenance zones based on maintenance limits

Model assumptions and parameter estimation

- This research aims to evaluate the track geometry degradation in the longitudinal level, by considering deterioration in subgrade as the dominant influencing factor for the track geometry quality. More particular, the track geometry index should be determined as a function of the subgrade condition.
- When the track geometry condition exceeds the maintenance limit for standard deviation in the longitudinal level, preventive maintenance (Ballast tamping) should be planned according to the model.
- Furthermore, the recovery effect of tamping has to be modeled to capture the track geometry restoration. Tamping action is also assumed to reduce the rate of degradation temporarily at the surface level; however, the subgrade condition continues to degrade over time, as tonnage accumulates.
- All data used for the integrated model is simulated and sampled from a different distribution.As the model is expected to generate simulated data, it is important to consider a certain level of randomness and uncertainty.
- The different degradation mechanisms should be integrated into a simulation model that can sample the evolution of the degradation process, using traffic intensity, subgrade condition, initial track geometry condition, and maintenance limits as input variables.

Track Geometry Degradation Model - Wiener Process

- The stationary Wiener process allows for simulating random degradation paths representing the evolution of track geometry by a linear increase over time with random noise.
- This Wiener process has continuous sample path and independent normally distributed increments.

$$Z(t) = z_0 + \mu t + \sigma W(t)$$

$$Z(t) = N\left(z_0 + \mu t, \sigma\sqrt{t}\right)$$

$$t = N\left(\frac{MGT/year}{4}, \frac{MGT/year}{4 \cdot 10}\right)$$

$$W(t) = N\left(0, \sqrt{t}\right)$$

$$\sigma \sim \ lognormal(log(\mu), 0.592)$$

Track Geometry Degradation Rate

$$\mu(t) = \alpha \cdot f(\mu_{Kz}, \sigma_{Kz}) + (1-\alpha) \cdot g(MGT(t) - MGT(nt))$$

$$f(\mu_{Kz}, \sigma_{Kz}) = \exp(\lambda_0 + \lambda_1 \cdot \mu_{Kz} + \lambda_2 \cdot \sigma_{Kz})$$

$$g(\Delta MGT) = \theta \cdot \Delta MGT$$

$$\theta = \frac{0.01}{2 \cdot 15}, \ \lambda_0 = -6.0912, \ \lambda_1 = -0.0193, \ \lambda_2 = 0.053$$

- The main contribution to the track geometry degradation rate comes from the subgrade condition.
- The degradation rate of geometry increase as the support stiffness decreases over accumulated tonnage between maintenance actions.
- The degradation rate effective at the ballast level will experience a short-term restoration, but will increase subsequently due to the continuous loss in track support stiffness in the subgrade.

Change in Track support stiffness

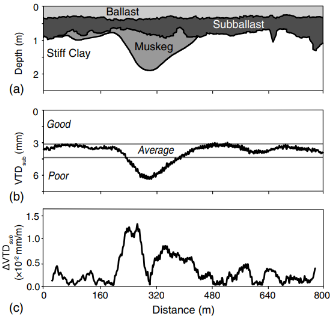
- Track support stiffness degrades over time with the accumulation of load.
- Standard deviation of support stiffness increase when mean support stiffness decrease.
- Change in track support stiffness affects the track geometry degradation rate.

$$\mu_{Kz}(t) = 159.98 \cdot \exp(-0.223 \cdot MGT(t)^{0.25})$$

$$\sigma_{Kz}(t) = 30 - 25.075 \cdot \exp(-0.007 \cdot MGT(t))$$

Initial Track Geometry Condition

- Mean and standard deviation of support stiffness
- Vertical track deflection in subgrade.
- Defects in longitudinal level (SD_{LL})



$$VTD_{sub} = \frac{(\mu_{Kz} - 40) \cdot (6 - 2)}{(160 - 40) + 2}$$

$$\Delta VTD_{sub} = \frac{(\sigma_{Kz} - 5) \cdot (0 - 1.5)}{(30 - 5) + 0}$$

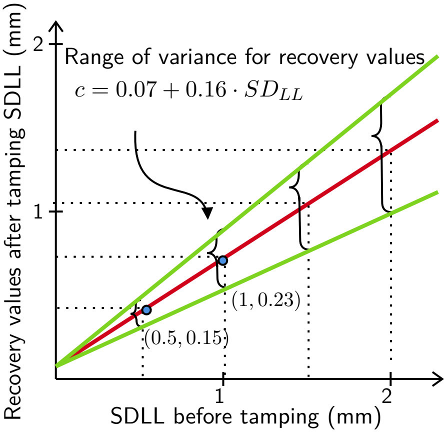
$$VTD_{sub} : [2 : 6]$$

$$\Delta VTD_{sub} : [0 : 1.5]$$

$$\mu_{Kz} : [40 : 160]$$

$$\sigma_{Kz} : [5 : 30]$$

Tamping Recovery Effect



$$R_{LL} = a + b \cdot Z(t) + c$$

$$d = 0.07 + 0.16 \cdot Z(t)$$

$$c = N\left(0, \frac{d}{4}\right)$$

Cost Model

- Total maintenance cost over degradation path.
- Number of inspections and tamping.
- Track Renewal is planned at the end of simulation.

$$C_{tot} = C_{ins} \cdot \sum(N_i) + C_{pm} \sum(N_{pm}) + C_R$$

$$\begin{aligned} C_{ins} &= 500DKK \\ C_{pm} &= 5000DKK/per.200m \\ C_R &= 100000DKK \end{aligned}$$

Multi-criteria Decision Analysis

The general structure of an MCDA is comprised of the aspects:

1. Set of available alternatives (Different limits for maintenance and renewal)
2. Set of criteria (Representing the characteristics of the alternatives)
3. The preference structure of the decision-maker (Reflected in criteria weight)

The following ranges define the total number of combinations (scenarios) evaluated by simulation:

- AL = [0.8:0.1:2]
- TF = [20:2.5:40]
- MGTyear=[5:1:35]

Analytical Hierarchy Process Model

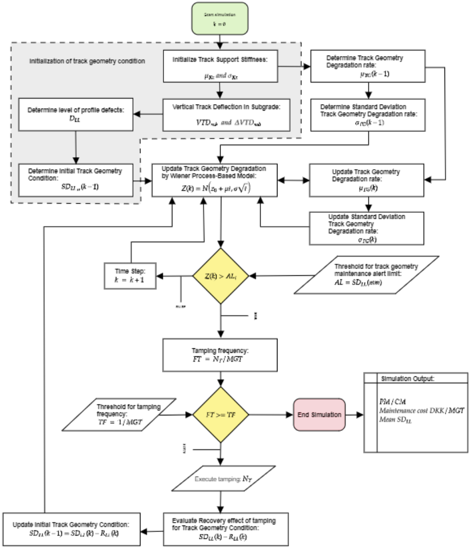
For this MCDA, the following criteria are considered:

1. Maintenance cost - that is a unit price describing the average cost of maintenance per. Million gross tonnes (DKK/MGT).
2. Mean SDLL - this describes the average standard deviation in the longitudinal level.
3. PM Ratio - This ratio is a risk indicator, and is estimated from the amount of standard deviation above and below the maintenance limit (AL).

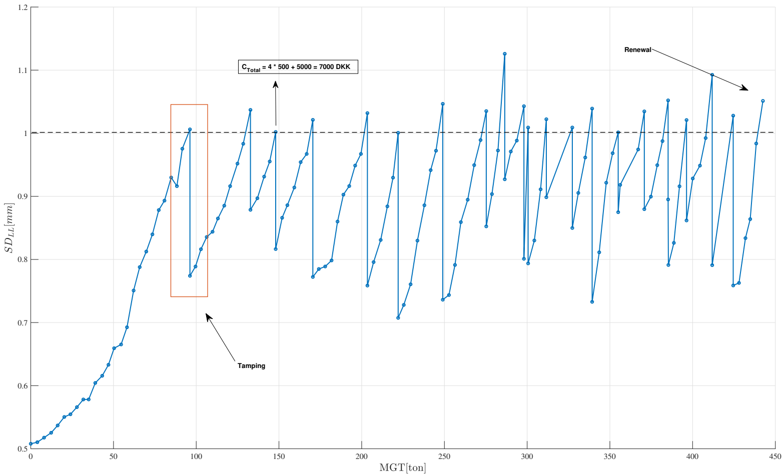
Pair-wise comparison of criteria:

Criteria:	Maintenance Cost	Mean SDLL	PM Ratio
Maintenance Cost	1		
Mean SDLL		1	
PM Ratio			1

Simulation Model



Track Geometry - Simulated Degradation Path



Track Geometry Degradation Rate

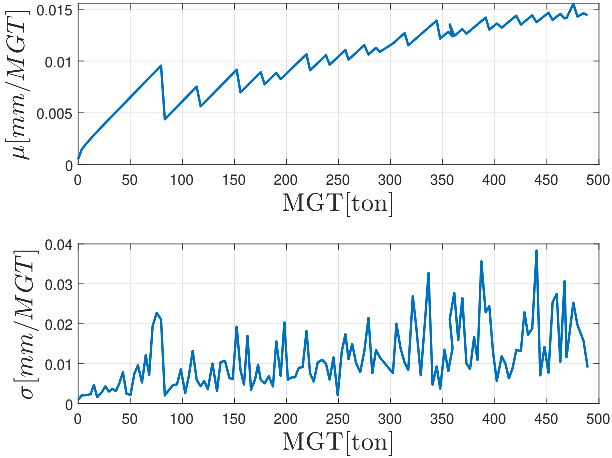


Figure: Evolution of track geometry degradation rate and variance

Track Support Stiffness

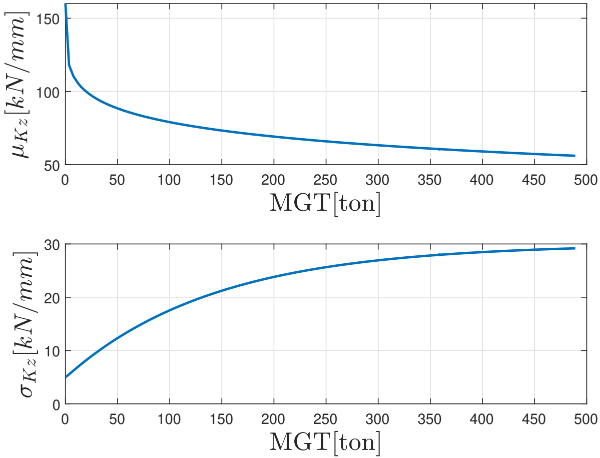


Figure: Track support stiffness mean value and standard deviation

Sample convergence of mean maintenance cost per. MGT

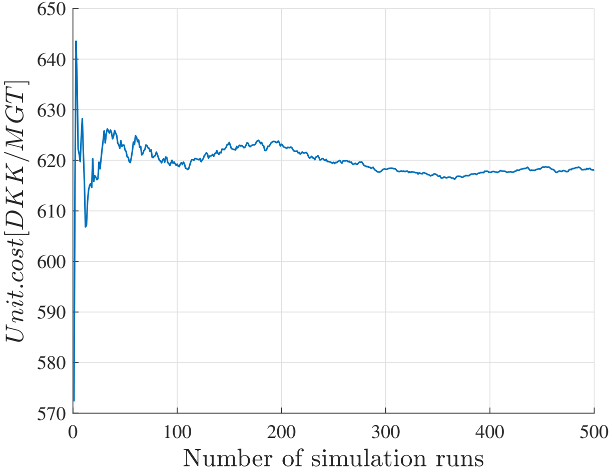
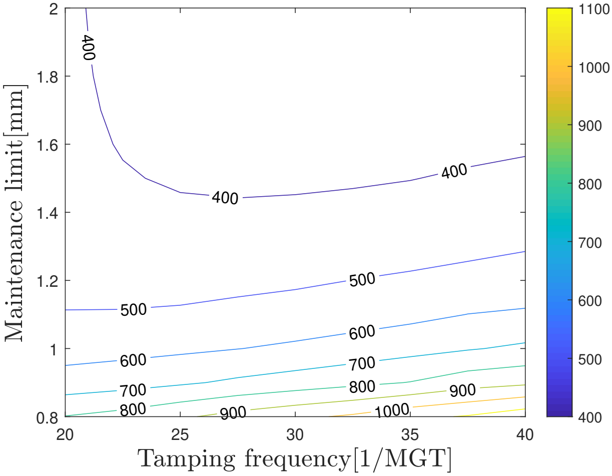
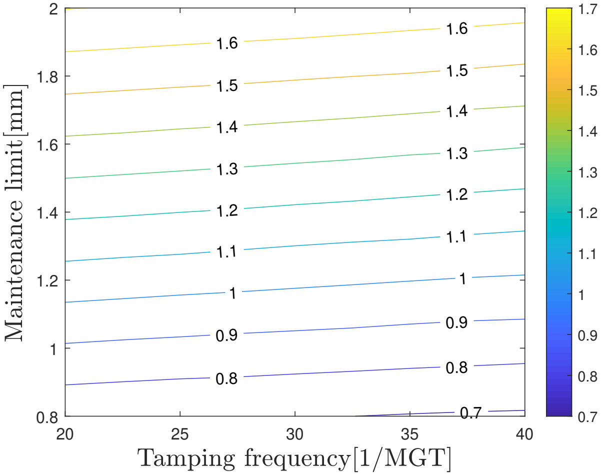


Figure: Sample convergence of mean maintenance cost per. MGT

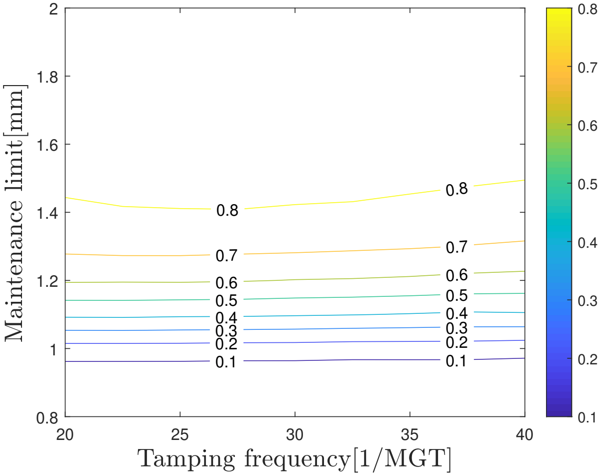
Contour plot for mean maintenance cost per. MGT for 15 MGT/year.



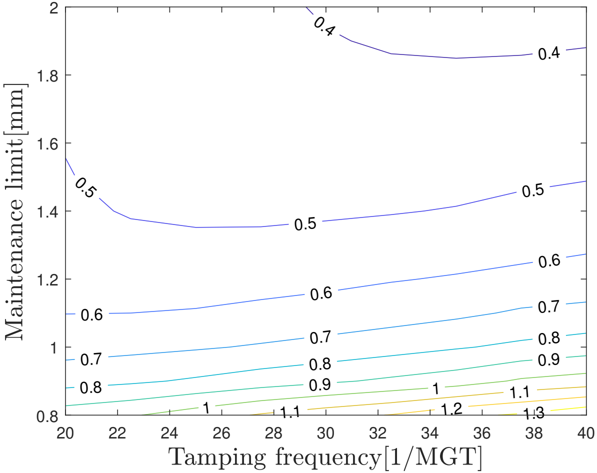
Contour plot for mean SDLL (mm) for 15 MGT/year



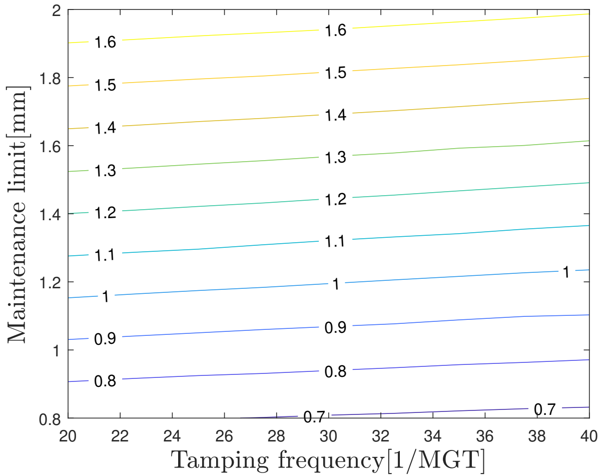
Contour plot for PM Ratio for 15 MGT/year.



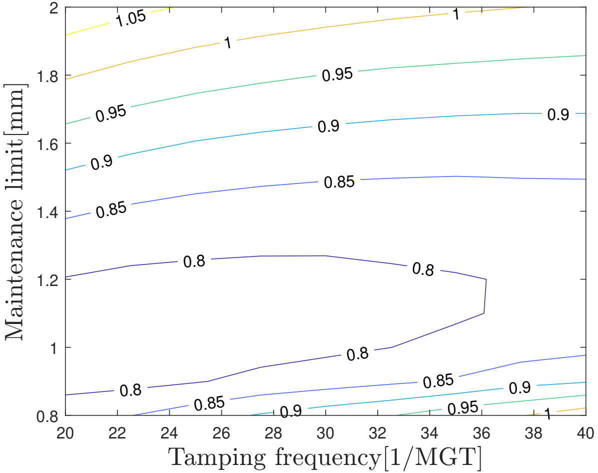
Contour plot for MCDA score with maintenance cost as dominant criteria



Contour plot for MCDA score with SDLL as dominant criteria



Contour plot for MCDA score with maintenance cost and SDLL equally weighted



Conclusion

- Evaluated the track geometry condition based on track support stiffness and track modulus.
- Propose an integrated degradation model to evaluate the track geometry condition based on subgrade deterioration while also considering the recovery effect of tamping.
- Introducing a threshold for track renewal, defined as 'Tamping frequency'.
- Developing a simulation model capable of capturing the degradation phenomenon and evaluating the effect of different maintenance limits.