Review Article

Maintenance Methodologies Embraced for Railroad Systems: A Review

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Congestion on land, hike in fuel costs, and critical need to cut down environmental emissions have generated the urge to shift from conventional rail transit systems to metro rail and high-speed rail for a mass mode of transportation. The conventional railway network especially in India stages an effective space in the means of mass transit systems. Subsequently, periodic inspection of the state of railway tracks is vital for ensuring rail safety, as tracks are critical components of train transportation networks. Tracks are designed to withstand zero critical incidents, and with the advent of new high-speed train services, there is a greater need to focus on track performance. Track maintenance methods are customized to suit local conditions for enhancing safety and reducing disruptions while guaranteeing the resilience and sustainability of any rail system. In recent years, various aspects of the TMSs (track maintenance systems) have been introduced within the railway industry for both ballasted and ballastless track systems. This study reviewed various approaches to track maintenance measures using traditional methods, statistical methods, and geometry-based methods based on track deterioration. Among all the reviewed methods, track maintenance based on the geometry is said to cater to the needs of the maintainers. The outcomes of this study are expected to support and assist in track maintenance decisions in the railway industry.

1. Introduction

Railways have always played an important role in the transportation of commodities and passengers. Massive consignments get transported through railways mainly due to their cost efficiency and reduced environmental emissions. Currently, most of the goods and commuters are shifted by this mode of transport increasing their loads and indirectly the tracks on which they run. Railway tracks on which trains run encompass switches, ballasts, sleepers, and rails, where ballasts are used globally in railway tracks [1]. Though slabs are also substituted in a few parts, ballasted tracks are conventionally used due to their reduced costs and ability to handle dynamic loads. Over years these ballasted...
trackless systems have been replaced by ballastless tracks. In a ballasted railway track, the ballast consists of crushed granular material. This ballast layer has sleepers embedded inside of it, which are used as a support mechanism for the superstructure. The ballast is placed on top of the sub-ballast. The ballast has many key functions such as supporting the weight of the track, absorbing and distributing loads (static and dynamic) of trains running on the tracks, and providing good water or fluid drainage capabilities [2]. The ballast also increases track stability in the lateral and longitudinal directions and, therefore, they must be maintained regularly. Throughout history, loads and speeds have been steadily increasing in rail transportation, and throughout this evolution, railway tracks have experienced changes. One such advancement is a full rebuild of track structures, which renders them ballastless. Traditional ballasts are replaced by firm supporting slabs consisting of concrete, steel, or asphalt, which transfers the load and provides stability. As numerous comparable components characterize them, there are several varieties of ballastless track systems available based on different manufacturers. As a stiffer alternative to ballasted track systems, additional precautions must be taken to maintain flexibility. A common feature embedded in most of the ballastless track systems is that they have highly elastic rail fastening systems. For further elasticity, other elastic components can be installed, such as pads, bearings, or springs [3]. The major advantages of using ballastless tracks are described as follows: large reduction in maintenance cost (20–30% of maintenance cost of ballasted ones), fewer traffic interruptions, contributing to higher availability, less restrictive use of electromagnetic wheel brakes, reduced structural height and weight, and preventing the release of ballast dust in the environment.

Figure 1 represents an overview of the ballastless track systems in practice within the Indian Metro Rail System. There are two approaches to express track conditions, namely track geometries and track structures. Track geometry flaws and irregularities are primarily used to represent track conditions and plan track repair. Track geometries deteriorate with age and use and can have detrimental impacts on track performances. When track parametric values fall below the satisfactory level, it causes derailment, with serious outcomes which may include increased railway operating costs, economic losses, damage to railway assets, the environment, and loss of human lives. Correction of inadequate track geometries results in expensive track maintenance. Their maintenance activities should be scheduled to restore track parametric values to an appropriate state. The state of rail transportation and track structures includes numerous components. Their service life and performances are primarily determined by maintenance techniques used throughout their life cycles.

Efficient rail infrastructure maintenance necessitates the correct allocation of resources to various operations, posing a number of practical and operational problems [4]. Maintaining railways can be categorized as follows:

(1) PM (preventive maintenance) involves carrying out activities (inspection, identification, and repair) based on periodic schedules where each equipment’s operating condition is checked and reconditioned.

(2) CM (corrective maintenance): all measures are taken if there is an unexpected or abrupt maintenance event in terms of repair of an item/equipment due to perceived faults by the users.

(3) PRM (predictive maintenance) is required wherever contemporary measurement and signal processing technologies are required to correctly anticipate and diagnose item/equipment condition during operation.

PMs are time-based activities for assessing track deteriorations and have been studied [5–7]. Though maintenance activities need to be preplanned and executed within a short time frame after on-site inspections, [85], it is difficult to plan them. Moreover, these operations disrupt sequences of regular PMs which keep railway track elements in tune and fine conditions. PM actions can assist to return the component to a better state, and they are frequently less expensive than component replacement [7–9]. To take advantage of the cost-benefit of PMs, a PM intervention can be performed a number of times repeatedly on a particular component prior to its renewal [10, 11]. As a result, track maintenance via a predictive process has traditionally been addressed as a series of independent phases, with each track component controlled separately. Various layers of management assess each stage for each key component of the rail system. Several studies have systematically classified various models and optimization models. The shortcomings in the field of track maintenance management have been highlighted, and future potential study fields have been recommended. The specifics of various track maintenance systems were investigated in terms of conventional approaches, statistical methods, geometry-based methods, machine learning methods, and bioinspired optimization methods in this review work. The track maintenance model’s best operational performance in terms of maintenance policy, maintenance cost, and reliability metrics is being evaluated and debated.

2. Overview of the Pioneering Analysis Undertaken in Track Maintenance Systems

2.1. Traditional Methods for Track Maintenance. Railway tracks are subjected to preventive as well as CMs. Among these, the PM’s activities are scheduled prior to providing a systematic way of monitoring the track performance. Various other numerical experiments were performed on track scheduling models by implementing superior computational methods, and these systems were applied to a railroad network to improve the maintenance schedule decisions where rail temperatures were focused. A study’s design included a heavy rail haul network of 60 kg/m using rail stress sensors, strain gauges, and thermocouples. The temperature of the rails varies regularly according to the temperature of the surrounding air. SFT might fluctuate by 2–3 times over the day, according to field experiments. Based on
these findings, an improvement in assessing track conditions using rail creep measurements was reported. TSMs (track stability management) are tools that identify requirements for PRMs. These tools stress the importance of rail stability and stress while defining rail modification priorities. Their assessments consider MS (margin of safety) or differences between TBs (track strengths) and TR–TN (rail stress) on the track. TR is the highest rail temperature while TBs are temperatures in which buckling might occur. TSMs use three elements, namely safety, track conditions, and prioritization of stress to obtain parameter values and act accordingly. RSMs (rail stress monitors) and strain gauges were installed on two (4 and 6 meters) 60 kg/m rails and tested with vertical loads of 5000 kgs where a hydraulic actuator was used. The test results were calibrated using finite element analysis. Computational results on strain gauges and thermocouples showed reduced SFTs at higher rail temperatures and contrary to RSM values which had increased SFTs at higher rail temperatures. Track maintenance decision support systems have also made use of computational approaches such as big data. Big data methods have been presented to help with railway track maintenance choices. A large quantity of data on railway track condition monitoring is being gathered from various sources in numerous countries. These data are not being properly utilized due to a lack of appropriate methodologies for extracting key events and critical historical information. As a result, important information is concealed by massive amounts of data from various sensors. For railway track condition monitoring, general approaches that may support effective track maintenance decisions are provided. In Dutch tracks, as a benchmark, axle box acceleration (ABA) measurements are utilized, and generic reduction formulae are addressed to manage failures [12]. Moreover, the risk matrix application focused on identifying track zones that were bottlenecks and limited the operating strength and standard of tracks. A critical analysis method was presented to generate a hierarchical
improvement list in order to solve the issue of train mission interruption and lower operational capacity. The study’s findings categorized the track line section into distinct risk zone categories based on their capacity and punctuality loss [13]. The process illustrates the analysis of track geometry simulation while optimizing the schedule with regard to tracking possession time as the research intends to decrease track possession cost. The analysis and modelling method for track maintenance planning and optimization will aid in the decrease of track possession time. Rather than maintenance schedule models, the bulk of studies on the tracks has focused on its deterioration process with regard to age and climate behavior. M&R (maintenance and renewal) was also targeted in a study that created a generic deterioration model by simulating track behavior. The model’s life cycle costing and numerical optimization techniques minimized costs by balancing maintenance or renewals and could also produce qualitative inspections including disruptions to traffic. The scheme assisted in achieving the global objectives of RMMSs (railway maintenance management systems) [14]. The proposed M&R approach connected inventories, work history, and resource allocations to automatically predict deteriorations. Two critical components of the proposed PMs were namely localizing defects in infrastructures and accounting for parameters that were uncertain in their prediction of future deteriorations [15]. Impacts of an EI (electrically insulated) railway junctions regarded as a vital asset for railroad track identification as well as a major source of train interruptions were also examined. The maintenance aspects were added to FMTs (fault maintenance trees) to determine the complexity and correctness of the parameters involved. The study’s findings indicated that it was feasible to enhance joint reliability, for example, by doing more inspections, but the increased maintenance costs exceeded lower costs due to failures [16]. Consumed time due to maintenance can be constant or may change. Hence, the minimum time required to maintain segments was targeted where maintenance schedules were modified based on three distinct variations.

The scheme CARPF (capacitated arc routing problem with fixed cost) has resolved these issues by considering the parameters as a node routing issue [17]. Most track maintenance programs are designed to save money or time, but very few are designed to decrease the downtime of the equipment used to accomplish them. This optimization approach aided in the early discovery of problems thus reducing equipment downtimes and increasing production [18]. The majority of conventional track maintenance approaches have focused on studying track behavior owing to deterioration and wear prediction models. Reference [19] presented a mathematical programming approach for modifying train schedules on a single track based on maintenance activities. The unpredictability of maintenance activities may cause delays in the original maintenance plan, which may also conflict with predetermined train schedules. By adding buffer time into the redesigned schedule, this study tackles the unpredictability of maintenance tasks. In the modified timetable, the operational restrictions via speed limit due to maintenance activities were also addressed. The model produces a revised timetable that contains a

| Table 1: Inferences of traditional track maintenance methods. |
|---------------------------------------------------------------|
| **Author Reference** | **Evaluation Scheme** | **Concentrated segment** | **Parameters involved** | **Tools employed** | **Research gap** |
| [20] Real time | Track maintenance schedule | Time window/travel cost/ penalty cost | Time-space network model | Running time/renewal cost of rail |
| [12] Case study | Track maintenance | Axle box acceleration measurements | Big data techniques | Maintenance frequency |
| [13] Case study | Track maintenance analysis and rail infrastructure | Railway track operational factors | Risk matrix modelling | Weak overhead cable |
| [14] Case study | Track deterioration | Track geometry measurements | RMMS | Life cycle costing |
| [16] Case study | Electrically insulated rail joint | Inspection time variations/ periodic replacement interval | Fault tree analysis | Inaccurate prediction/ frequency of usage |
| [17] Case study | Track maintenance schedule | Time periods/set up cost/key performance indicators | Capacitated arc routing problem | Maintenance crew scheduling |
| [18] Case study | Track fault detection | Temperature/current/ voltage | Remote condition monitoring | Database management/ decision-making |
| [19] Real time | Track maintenance schedule | Train timetable | Mathematical modelling | Speed restrictions |
| [21] Real time | Track buckling | Rail temperature | Finite element analysis | Weather parameters |
| [22] Case study | Rail maintenance | Squats/ballast defects | MILP solver | Multiple track defects (corrugation/ballast degradation) |
maintenance plan and train operation schedules for railway planners. Table 1 summarizes the conclusions drawn from traditional track maintenance methods:

The findings from conventional practices have revealed the usage of Weiner process, undirected graphical method, and fixed location-based monitoring method by the researchers for track maintenance practices. Many other methods like mixed integer linear programming (MILP) model, reliability-centered maintenance signalling system, and global sensitivity analysis based on distribution technique were utilized for forecasting and assessing track performance and resilience [15, 23]. With the introduction of metro rail transit systems, most of these methods are no longer extensively used. The majority of the studies mentioned above were well suited for the conventional railway system; thus, there is a need to use sophisticated prediction methods and forecasting models for track preventative maintenance.

2.2. Statistical Methods for Track Maintenance. Most of the statistics-based maintenance techniques are catered to create models or optimizations. Track geometry was predicted by [24] based on Petri nets. Their study projected conditions of the track with their estimated lifetime costs. The study altered inspection, maintenance, and ballast renewal parameters to achieve efficient predictions. Maintaining high-speed rail corridors using shared/dedicated operation patterns was examined, where descriptive parameter tables analyzed a corridor’s response to changes in track maintenance strategies [25]. A modelling technique assessed existing data on track geometry and ballast condition, collected at regular intervals. Using the provided degradation distributions, a track section model was created that integrated maintenance and renewal processes and allowed the prediction of the ballast section’s state over time frames. The model employs a Petri net formulation with a Monte Carlo solution routine to examine the efficacy of various maintenance techniques [26]. Most of the track maintenance schedules corresponded to train timetables. Several studies have modified the railway schedule based on the repair schedule. Physical inspections and visual examinations were the base for assessing track geometry issues. The scheme pointed out discrepancies in inspection data of tracks using a specialized instrument (track geometry vehicle). The model eliminated all positional errors from inspection data irrespective of noises in parameter measurement values. The model took $1.5004 \text{s}$ to correct $1 \text{km}$ track segment’s positional errors. Further, the model also adapted itself to a variety of other applications: track geometries of trolleys, highway inspection data from LiDAR (Light Detection and Ranging) vehicles, and railroad catenary wire geometry inspection [27]. Despite periodic maintenance and considerable noise, the results line up exactly. Grindings are used in this study to eliminate fractures based on their depth. The rate of expansion of cracks on the head rail remains constant and the crack grows by $1\%$ for every $1\%$ increase in ridership [Mega gross tons]. It is expected that a single machine pass can repair a crack with a depth of $h \text{mm}$ and a cost of $ascg$. The increase in track growth was represented by a typical track section with the final limit as $Ti$. If the length of the track segment $I$ exceed the limit $Ti$, the track is replaced at a cost $cr >> cg$. An increase in rate correlates with a decrease in the duration of cost function intervals. The last PMs are to be replaced at a higher co at the limit $Ti$. Similar research was proposed for solving issues in interactions between high-speed night trains and maintenance schedules by utilizing MILP solver. The study rearranged maintenance schedules to accommodate high-speed night trains running early morning or late evenings resulting in enhanced maintenance plans and timetables [28]. The midnight train timetable typically overlaps with the daytime train repair schedule. The service line is closed during maintenance of any railway section; therefore, to avoid conflicts, the maintenance period for specific segments is shortened to less than 4 hours or postponed accordingly. Night trains utilize the spare time available between consecutive railway segment repairs ($G$). In order to avoid the conflicts between the train schedule amidst the maintenance schedule, certain trains were even cut off from service line. Thus, the work presented a modular approach for railway maintenance schedule optimizations.

A predictive technique for railway track maintenance scheduling was implemented taking into consideration risk assessment strategies based on ISO 55000 standards as well as real-time track conditions. A unique feature of this method is the inclusion of the idea of risk management in railway maintenance scheduling, suggesting that maintenance activity priorities are based on asset criticalities, such as track degradation conditions and repair prices, as well as users’ unmet demand caused by asset failures [29]. To deal with nonlinearity concerns, predicted track degradation models are used. Tracks are classified into four conditions: good where there is negligible degradation, waiting maintenance where the tracks are close to failure but the degradation process has commenced, acceptable track degradation where failure is expected to take place within $ds$ time, and unacceptable degradation level where the tracks are expected to be renewed or replaced. As a result, a MILP approach integrating cost, hazards, and appropriate weights is developed to forecast correct maintenance priority within a time horizon. The asset management approach used on a railway track segment was investigated using a Markov model. The number of model parameters employed forecasts the condition of a track segment over time for a specific asset management approach in order to illustrate the effects of maintenance interventions on the track’s lifetime. The Markov model offers a simple yet effective mechanism for evaluating the effects of an asset management strategy on a railway track section [30]. Tracks are classified according to their standard deviation (SD), namely $\delta$: good, $\delta$crit: critical, $\delta$spd: speed restriction, and $\delta$cls: line closure. Once a track section reaches $\delta$crit, the section requires maintenance. As the track deteriorates more, the SD value obtained will strike $\delta$spd, implying that speed limitations will be applied to that portion. In case of further deterioration, the track segment reaches $\delta$cls which indicates there is an immediate need for closure of that segment. Theoretical prediction of track
irregularities was proposed by [31]. The study’s grey model was compared with linear and exponential models. The study computed longitudinal standard deviations with the use of regression while their grey model was based on inspection data. In their assessment of prediction accuracies, the study found that modifying their model using the Fourier series resulted in the best performances with minimal errors. The work was an asset to the planning and scheduling of PMs. In addition, track inspectors were used to undertake an enhanced method of track geometry monitoring as data related to tracking geometry behavior was manually captured. After the advent of modern rail track inspection vehicles, this had altered as the vehicles run along train tracks and collected data about the state of infrastructures. Based on this information, a degradation model for train tracks was built in order to anticipate track deterioration and estimate future maintenance operations. To forecast tram track degradation, an ANFIS (adaptive network-based fuzzy inference system) was proposed where ANFIS estimated gauges. The system was found capable of accurate predictions even in jumbled data [32].

PMs were scheduled by [33] using optimization on a combination of PMs and renewals and arriving at the best between them. Resource optimization solutions such as grouping and balancing are used to reduce maintenance costs while maintaining the same level of service. Mixed integer linear programming is used to lower the costs of maintenance and renewal projects, as well as the associated labor and downtime charges, across the planning horizon. According to experimental data, the integrated optimization strategy minimizes the cost of preliminary work by effectively arranging it. The combined strategy resulted in a 14% reduction in maintenance and renewal expenses. Another research on preventative maintenance schedule was recommended to keep railway infrastructures in excellent working order while also taking into consideration limited resources available. The challenge of scheduling preventative railway maintenance operations was defined using MIP (mixed integer programming) and VNSs (variable neighborhood searches) to address large instances of the problem [34]. Many studies have focused on preventative maintenance scheduling techniques, while only a few of them focused on CM scheduling. Following their discovery as part of an inspection procedure, a methodology was presented in the study for optimizing CMs in rail networks. A study modelled integer programming for minimizing passenger delays due to low operational speeds on degraded rail segments while giving importance to intensively operating segments, train loads, staffing, budgets, and other constraints [35]. Figure 2 shows the degradation of rails, which was monitored on a real-time basis. These figures represent the lack of greasing along the sliding chair of check rails, rusting of check rail locks, worn-out base plates/rail plates that control the friction between the eccentric bushes and the anchor bolts, and the lack of greasing in the nosing areas. These defects indicate high chances of track slips that might create pits on the tracks thereby causing damage to the rolling stock.

The idea of RAMS (reliability, availability, maintainability, and safety) has been embraced by most metro rail depots, and a similar approach was recommended to assist choices on train track design and maintenance methods. RAMS management is often used in the railway industry, but the proposed LCCA supported decisions on design alternatives and maintenance methods through an economic analysis that considered costs and performances. As a result, a decision support system was created based on life cycle costing (LCC) analysis for balancing immediate and long-term costs with performance and targeting RAMS. The suggested model incorporated not just agency (e.g., construction, inspection, maintenance, and renewal) and user expenses (e.g., delay-related) but also environmental costs into a full life cycle cost analysis (e.g., related to CO2 emissions). The RAMS of a slab track was typically greater than that of a ballasted track, according to the findings [36]. A comparable analysis of life cycle costs was recently offered as a reasonably inexpensive alternative maintenance strategy for existing lines. This research seeks to evaluate the technology’s potential benefits while also developing a new maintenance approach for existing ballasted rail beds. A protocol for the use of the BSB technology, as well as its related maintenance plan, has been established. The acquired results are also submitted to a sensitivity analysis. The use of BSS is projected to result in a considerable increase in the time between minor and major maintenance tasks [37]. Using the binary integer programming (IP) paradigm, a study has proposed a maintenance schedule optimization model for various components of a railway track. In general, grouping and maintaining several track components under one ownership saves the cost incurred as the track tends to be occupied. A sensitivity analysis is used to emphasize the effects of available possession time on the number of necessary possessions as well as the total cost involved [38].

In the same way as the prior integer programming model [39], a MIP model for routing vehicles with restrictions was proposed targeting Class-I railroads. Very few or limited studies have explored MDMs (Markov decision models), but one study used MDMs to obtain predicted values as impacted by present scenarios. The proposed MDMs used the train wheel’s distinct conditions including their diameter, renewal distance based on time, and damages based on conditions. The study’s estimated Markov transition matrices considered PMs and proposed an optimal strategy for ideal actions based on wheel conditions/states [40]. Another study was also based on MDMs and used conditions of the rails to define an optimal strategy that reduced overall costs. Rail conditions were assessed by the MDM using height, weight, MGTs (million gross tons), and damage incidences of the rails. The proposed optimum policy was a set of three PMs for railway managers to decide on the best PMs based on the state of the rail [41]. MPCs (model predictive controls) were proposed for multilevel decisions on optimum railway network’s PMs. The study differentiated sections using independent stochastic degradations. They used a controller to compute and arrive at long-term section-wise PMs, thus helping reduce deteriorations and maintenance costs while ensuring degradations did not cross a defined threshold. The study’s Dantzig–Wolfe decompositions optimized both continuous and discrete variables for best
decisions. Short-term schedules for maintenance using a high-level controller were proposed where maintenance staff routing was optimized. The study handled the issue assuming it as a routing issue and was found to be resilient, nonconservative, and scalable in simulations. Maintenance was scheduled based on average deteriorations and maintenance threshold values. The maintenance plan for certain sections had raised above maintenance thresholds and had to be grounded to zero after 6 months. In case of maximum deteriorations, time steps near maintenance threshold values and this occurs only during rail breakages. Table 2 lists the inferences obtained from the statistical maintenance methods. Most of the statistical methods employed for the maintenance of tracks have left a leap in the area of renewal cost.

2.3. Maintenance Methods Based on Track Geometry. Bayesian models are probabilistic models that are thought to describe the connection between conditionally independent and dependent variables. Only a few investigations have been using this technique to evaluate rail track geometry deterioration over time in order to improve rail track geometry degradation uncertainty. Inspection historical data were used to assess uncertainties and were updated after every inspection. After each update of inspection history, uncertainties were assessed and degradations were measured by computing subsequent probabilities [42]. Similarly, the same approach was used to forecast and track deteriorations for guiding maintenance/renewals. This study used conditional auto regressions on track geometry data for interactions between successive track sections and lines [43]. The study simulated multiple correlations in consecutive track section components including degradation rates using HBMs (hierarchical Bayesian model). Their HBM assessed quality by comparing sensitivities of their generated candidate model’s past distributions. Reference [44] used HBMs to evaluate railway track deteriorations. In addition, the model’s initial block is made up of rail deterioration, followed by the second block, which is made up of n number of elementary rail sections, developing a maintenance model for the entire stretch is considered unrealistic. As a result, the model only represents the elementary rail sections, which are extrapolated to larger sections based on reliability indicators. The VirMaLab model can estimate track degradation from hour to hour, including the effects of broken rail during peak hours. According to the VirMaLab Bayesian network, each condition of the rail is classified as OK (the rail with null defect), X1 (rail with internal cracks that are larger than 2 mm), X2 (rail with both internal and surface cracks less than 30 mm large), or BR (broken rail). The model’s initial block is made up of rail deterioration, followed by the second block, which is made up of diagnosis devices. Ultrasound vehicles (USV), walking survey teams (WT), metro drivers (Drv), and track circuits are the devices that trigger periodic rail changes based on traffic, peak hours, and operational stops (TC). TC is thought to be the first to discover 80% of the broken rail problems. In the case of a warm season, rail dilation aids in maintaining electric...
contact with the BR, reducing the capacity of the TC to identify a fault by 50% [46]. Stochastic models are financial models that predict the likelihood of obtaining various outcomes under various limitations using randomly chosen variables. These models are used to characterize the process of geometrical track deterioration over time. For each vehicle speed category, a statistical analysis is carried out. The novel aspect of this study is that the Dagum distribution, which is commonly used to depict income distributions, is used to represent the geometrical track degradation process at the longitudinal level [47]. As part of condition-based preventative maintenance, a stochastic mathematical model is being created to optimize and anticipate tamping operations on ballasted rails. The model is described as a mixed 0–1 nonlinear program with real technical restrictions such as longitudinal standard deviation deterioration rate, track layout, track recovery dependency on its quality at the time of the repair operation, and preventative maintenance limits. This model looks at a 51.2 km long section of railway during a 10-year period. The deterioration model was found to be stochastic in nature, and it displayed the longitudinal standard deviation decreasing with time. The rate of degradation of the longitudinal standard deviation was modelled using Monte Carlo techniques, with three parameters taken into consideration. Dagum’s probabilistic distribution blended well with real-world data. The results of two simulations, namely stochastic simulation in space and time, were compared to one another. [48] The suggested condition-based maintenance model could provide optimum schedules in a reasonable amount of time. Only a few other researchers have focused on establishing an analytical framework that aids in decision-making. Reference [49] provided an analytical methodology for determining the best geo-defect repair options by minimizing anticipated costs including derailments/repairs. The study’s major contributions were in integrating three models: track deteriorations of Class II geo-defects; survival of tracks from derailment risks, and optimization of track repairs under uncertain conditions. The proposed models showed a 20% reduction in overall composite costs and the percentage rose when longer track sections were considered.

Another study that followed this proposal using the same approach except that their model was an optimization was based on cost-based formulations and risk-based formulation (RBFs). These schemes addressed optimal rectification

| Author Reference | Evaluation Scheme | Concentrated segment | Parameters involved | Tools employed | Research gap |
|------------------|-------------------|----------------------|--------------------|--------------|-------------|
| [5] Case study | Track maintenance | Frequency of tamping operation | Mixed integer programming model (MILP) | Cost structure/schedule generation |
| [6] Case study | Track maintenance | Rail grinding schedule/rail crack detection | Integer programming model (ILP)/polyhedral analysis | Maintenance decision-making process/frequency of inspections |
| [24] Case study | Track geometry | Inspection/intervention/renewal | Petri net formulation | Track length/tamping machine |
| [25] Real time | Track maintenance | Segments/routine works/possession cost | TMS strategy/Sensitivity analysis | Calibration of the PMSP model |
| [29] Case study | Track maintenance schedule | Maintenance activities/risk assessment | Modular model architecture/ILP | Online recovery tool to determine stochastic delays |
| [32] Case study | Track degradation | Rail load, rail type, rail profile | Adaptive network-based fuzzy inference system (ANFIS) model | Gauge value prediction |
| [33] Case study | Track maintenance | Time period/track component replacement | Integer programming model (ILP)/Heuristic algorithms | Unexpected interventions/corrective maintenance decisions |
| [36] Case study | Track maintenance | User cost/environmental cost | RAMS/LCCA | Database management |
| [37] Case study | Track maintenance | Ballast type/lab test/traffic | Life cycle approach | Life cycle cost analysis (LCCA) and life cycle assessment (LCA) |
| [38] Case study | Track maintenance | Rail, ballast, sleepers, and switches | Binary integer programming (IP) model | Limitation of possession time |
| [39] Real time | Track maintenance clustering | Project duration/job cluster type | Mixed integer mathematical programming model (MIMP) | Randomness of algorithm |
| [40] Case study | Track interactive rolling sets | Wheel diameter/mileage | Markov decision process/MDP toolbox-MATLAB | Markov transition matrix (MTM)/inspection modes/precision |
| [41] Case study | Track maintenance | Rail grinding/renewal | Markov decision process | Rail curvature |

Table 2: Inferences of statistical track maintenance methods.
planning challenges of railways. To improve track rectification decisions, existing railroads are presented with decision queries such as how yellow tags slip into red tags, how unrectified yellow tags slip into the risk of derailment, and what should be the correct time horizon within which an activity is prevented from falling into the red tag area [50]. Because track geometry is regarded as a hotspot in any railway industry, few research have focused on the degradation of track geometry by utilizing the Weibull technique and regression approaches. Reference [51] presented a Weibull method for analyzing time distributions for track geometry to deteriorate to defined states after repair. The quality of the track is determined by the rail alignment, particularly the vertical alignment. Higher wavelengths that have little bearing on ride quality are filtered out. The train engineers use a wavelength filter of around 35m to screen the track condition. The standard deviation for a 220-m yard segment is then determined. In addition to the tamping action, the quality of the track geometry is assessed. The findings of this study demonstrate that traffic speed and the history of any line’s maintenance have an impact on geometrical degradation. Furthermore, the notion that tamping affects railway ballast is supported.

Meanwhile, [52] used a logistic regression technique to add unplanned maintenance requirements for rail track geometry deterioration. Unplanned maintenance for tracks based on European Standard EN 13848 was proposed in a study. The study considered bridges and switches data from inspection records and analyzed them statistically. Standard deviations from longitudinal values and errors in horizontal alignments were used as main indicators for unplanned maintenances. The study also proposed trade-offs between planned/unplanned maintenances and catering to EN 13848 limitations. Most optimization approaches focused on track conditions and costs of renewing them. PMs were forecast using biobjective optimizations where renewals were linked to track geometry. From the standpoint of infrastructure management, the challenge was treated as an objective integer optimization problem. The overall expenditures of planned repair and renewal activities, as well as the total number of delays in runtime induced by speed limits, were both minimalized. The optimal Pareto frontier was determined using a simulated annealing approach in a tiny example for a basic network [53]. In a railroad track degradation study, [54] developed a short-range track condition forecast technique. Its purpose is to inform railway maintenance managers about the track condition ahead of time so that track maintenance activities may be scheduled. Track geometrical exceptions are derived from track conditions assessed using track geometry vehicles, and the projected values revealed that they did not offer a trustworthy condition. Track geometry data from Jiulong-Beijing train track geometry cars were used for error and comparability tests. The improved model is strong enough to generate trustworthy predictions, according to the analysis results. Reference [55] suggested a new approach for forecasting track geometry defects that is comparable to existing track records and combined prediction with inspection and maintenance planning. Broken rail faults are frequently preceded by visual and ultrasonic cracks. The recommended strategy’s underestimation of flaws is controlled by a novel application of a risk-averse and hybrid prediction approach.

MDM forecasts identified suitable inspection and maintenance strategies. Moreover, Whittle indices using an updated transition kernel (multi-bandit formulations) offered optimum dynamic policies to handle limitations. The study forecastings were highly accurate and suitable to forming long-term scheduling rules which could be changed based on changing conditions. Reference [56] reduced ballast costs for maintenance/unit traffic by their optimization of track geometry inspections. The study considered inspection and maintenance timings along with incurred costs for inspections, tampering, and risk of accidents based on track conditions. The study’s probabilities were based on northern Sweden’s track geometry data where passenger and freight trains were considered. Constructions, operations, designs, and maintenance account to track geometry degradations. Reference [57] assessed PM limits for Iran’s railway lines to reduce overall maintenance costs. The study’s cost model included PMs, CMs, inspections, and penalties when CMs limits were exceeded. The study used standard deviation values of longitudinal levels for quality of railway geometry assessments. The study minimized model’s uncertainties in maintenances. The most comparable track sections were classified using the K-means clustering method. Thereafter, a linear function was used to indicate the degradation of rail sections for each cluster. To anticipate track geometry behavior and calculate the appropriate maintenance limit that minimizes overall maintenance expenditures, the Monte Carlo approach was utilized. According to his results, putting in place an adequate limitation can save overall yearly maintenance expenditures by 27 to 57%.

Among the previously described track geometry models, [58] proposed a method for allocating an effective track geometry maintenance limit that results in the lowest overall yearly maintenance cost. The cost model integrated inspections, PMs, CMs, and emergency CMs using standard deviation and outlier values of singular faults on longitudinal scales to derive quality indicators for PMs and CMs. The study used Monte Carlo approach to model track behavior after maintenance operations, limiting it to certain scenarios thus minimizing overall maintenance costs. Sensitivity analysis on inspections and maintenance response times was used to suggest effective restrictions in railway operations. However, the study proposed a lower bound optimal value for operations. Track geometry is evaluated at discrete time intervals (s) to determine its condition, as previously indicated. Each inspection interval measures the standard deviation of the longitudinal level (DLL), and if it exceeds the action limit AL (DLL AL), the track will be examined for PM tamping during the first maintenance window (Ttamp). This means that PMs will not be performed on the track until the predetermined PMs period has passed, even if the DLL between two maintenance cycles is greater than the AL. Track geometry is evaluated at discrete time intervals (s) to determine its condition, as previously indicated. This study concentrates on the efficient determination of maintenances,
and catering to isolated faults has been outlined for future scope. Examining reaction times of regular CMs, track degradations can be categorized into normal tracks in CMs or CMs in an emergency. The categorization can be applied only when the time taken to react exceeds inspection intervals. In this study, the degradation of track geometry was modelled using a linear model and the degradation parameters. The degradation parameters in the suggested degradation model are (???? and bs) considered as random variables. The difference between the projected value and the measured value is said to be degradation, where t is the time in days and \( t_0 \) is the time at the most recent tamping operation. Various parameters encompass degradations resulting in a change of behavior in track sections. The AD (Anderson–Darling) test found suitable distribution where the likelihood of degradations assisted in estimating distribution parameters. It can be inferred that linear model residues get distributed normally in tests. Minitab software computed mean and variances of degradation model’s errors [58].

The increasing trend observed in the track length is represented in Figure 3 which indicates the critical need to monitor track geometry. Datasets related to track geometry cannot be easily obtained since they are not kept in a repository. Despite the fact that data gathering is uncommon, a few real-time studies have been developed and carried out using data-driven models, and a few of them are discussed here. Based on track quality evaluations over time, [97] developed a data-driven tamping forecast. A study database comprising asset information completed maintenance activities and measured data over a 4,400-km stretch of the Austrian rail network during a 16-year period has been made public. For planning and anticipating tamping operations, the modified standard deviation of vertical track geometry has been found as an excellent track quality indicator. Further analysis reveals that a linear regression function is most suited for characterizing track quality between two tamping activities and for forecasting track quality in the future with the highest accuracy. The linear regression function was used to create an algorithm that allows for the analysis of track quality behavior over time for large time series and the whole network. Based on measurement data gathered from the field study, a comparable data-driven analytical approach for prediction of isolated track geometry problems was created. A new defect-based model was suggested to determine the deterioration pattern of isolated longitudinal level faults of railway tracks. In the deterioration route, the suggested model considered the occurrence of shock events.

The efficiency of tamping intervention in correcting longitudinal-level faults was also investigated. The results demonstrate that the linear model is considered to be a good fit for exhibiting the longitudinal-level defect of the track degradation pattern. In addition, a section-based model based on binary logistic regression has been created to forecast the likelihood of isolated faults occurring in segments of railroad systems. As explanatory variables, the model included standard deviation and kurtosis of longitudinal levels. The kurtosis of the longitudinal level is a statistically significant predictor of individual track section levelling problems. The validation findings show that the proposed binary logistic regression model can detect the presence of isolated defects in a track segment with high accuracy [59]. Table 3 groups the inferences from the geometry-based maintenance techniques.

3. Identification of Real-Time Constraints in the Indian Metro Rail System

PMs are carried out by the maintainers in every Indian metro, and the values obtained at every section of the rail are recorded manually in registers which will further be verified by the section engineers.

The section engineers are responsible for deciding if any maintenance is to be performed by their team at the particular section after obtaining a work permit from the operation and control center of the railway. Therefore, there is a time-lapse analyzed here and this, in turn, may sometimes result in an emergency maintenance requirement. To offer a realistic prediction for track maintenance restrictions and real-time constraints, the most modern PMs for railway tracks rely heavily on inspection and degradation evaluation. To solve these constraints, recently several algorithms have been introduced which are discussed in the above section. The majority of the studies have concentrated on optimal routes for the maintenance crew, rerouting of vehicles as per maintenance schedule, clustering track maintenance jobs, cost for undertaking the early and late maintenance tasks, corrective maintenance programming model, considering actual infrastructure condition, minimizing the maintenance cost while maintaining the tracks at acceptance fit levels, minimizing the track possession time, and track degradation models. To the best of our knowledge, the major constraints encountered along the maintenance of tracks [Figure 4] are climatic conditions, lack of automated schedule, equipment availability, labour availability, track restoration time, block time, availability of parallel department, unskilled outsourced labor, implementation of additional stretch, budget constraints (hidden), maintenance tender, rail availability, train rerouting, trip frequency, material availability, budget approval time, and material processing time. The on-site constraints observed during the preparatory works of this study are as follows: outsourced technicians and maintainers-technical barrier, lack of preplanned maintenance activity, lack of systemized track maintenance schedule incorporating the constraints, climatic hindrances to complete the allotted activity, and lack of integrated (rolling stock, signaling) track maintenance scheduling.

4. Workplan for Future

Track maintenance system of Indian metros is possibly done during night time as the run time of metro train
begins every day on an average at 6:00 AM and ends by 9:30 PM and therefore the time slot available for preventive track maintenance is only during night time after all train sets are back to stabling sheds. The work time available for any track maintenance activity is hardly 4 hours. The maintainers walk along the planned sections

![Figure 3: Increasing trend of metro rail track length](source: https://en.wikipedia.org/wiki/Urban_rail_transit_in_India).

### Table 3: Inferences of geometrical track maintenance methods.

| Author Reference | Evaluation Scheme | Concentrated segment | Parameters involved | Tools Employed | Research Gap |
|------------------|-------------------|----------------------|--------------------|----------------|--------------|
| [7]              | Case study        | Track maintenance    | Track alignment defects | Decision support systems | Probability prediction of alert limits |
| [8]              | Case study        | Track maintenance    | Total cost/renewal actions/speed restrictions | Mathematical modelling | Degradation parameters/different network configuration |
| [9]              | Case study        | Track maintenance    | Track alignment parameters | HBM/Monte Carlo Simulation | Model sensitivity/correlation of formulation |
| [10]             | Case study        | Track maintenance    | Track alignment parameters | Markov decision process | Permissible speed restriction |
| [15]             | Case study        | Track maintenance    | Track alignment parameters | Weibull approach | Improvement of TPI |
| [47]             | Case study        | Rail maintenance     | Rail parameters | VirMaLab/Bayesian models | Integration of meta-heuristics |
| [51]             | Case study        | Rail maintenance     | Location/time of defect occurrence/defect type | Markov decision process/Whittle indices | Crew assignment for maintenance operations |
| [57]             | Case study        | Track maintenance    | Rail type length/allowable speed/ballast type/fastener type/passenger capacity | Monte Carlo simulation/K-means clustering algorithm | Reduction of maintenance cost |
| [58]             | Case study        | Track maintenance    | Maintenance window/frequency of inspection | Monte Carlo simulation/sensitivity analysis | Increase frequency and response time for maintenance |
| [59]             | Case study        | Track maintenance    | Track geometry inspection values | Heuristics/analytical framework | Time optimization |
| [60]             | Case study        | Track quality        | Track indices/longitudinal level | Linear regression analysis | Best fit integrated model |
| [47]             | Case study        | Track maintenance    | Longitudinal level, alignment, gauge, twist, and cross-level | Dagum distribution | Fitness of the model for varying track components |
| [48]             | Case study        | Track maintenance    | Track alignment levels/standard deviation | Mathematical modelling/MILP/Monte Carlo process | Maintenance cost |
of tracks and inspect visually during the nighttime which is very difficult at times to predict the exact track geometry measure. Most of the metro rail system has a parallel line known as a walkway along which the keyman can walk to inspect the lines in case of any reported issues observed during daytime. With the increase in track length, this is considered to be a critical task. In order to reduce the construction space and cost, walkways have not been included in any further projects. Therefore, in order to avoid a time-lapse in taking speedy action at the segment which requires immediate attention, a maintenance management model is believed to serve the purpose. Usually, the track geometry values are entered manually and recorded in separate registers. The section engineers in turn further check for the value accuracy and decide upon any need to directly inspect the particular section that has deviated from the tolerance/permissible value limits. There occurs a time-lapse for carrying out the maintenance activity, in case there is a need for immediate attention. Hence, it is necessary to have a planned scheduling system for allotting the maintenance activity along the track sections in between the service run during day time. As the Indian metros are on the verge of expanding their operational routes with a greater number of depots for stabling, it is highly necessary to plan the track maintenance activities systematically. Therefore, from all the previously referred reviews and methods, it is understood that most of the studies have been carried out on a real-time basis and the developed models are deployed into the respective systems to acquire better results. Through this work, the authors of the study have planned to develop a track maintenance alerting system for the Indian metros by developing a track cloud which will have a predefined set of datasets from historical records. This database acts as a base layer to identify the difference in parameter threshold values if they fall beyond the limits. The developed system will serve as a decision assistant to the maintainer who can determine whether the track requires immediate attention or not which will then be reported systematically to the policymakers.

5. Conclusion

Railway infrastructure is one of a country’s most valuable assets in terms of passenger and freight transit. The track is an essential aspect of the railway system among these components. As a result, maintenance planning for a busy railway track is difficult due to increased strain on increasing operation time, which limits the infrastructure-accessible time for repair. As a result, track maintenance has traditionally been regarded as a series of processes, with each track component being administered independently. Each phase for each major element of the rail system is evaluated at various levels of management. This review work studied the details of various track maintenance systems in terms of conventional methods, statistical methods, and geometry-based methods. The best operating performance of the track maintenance model with respect to the maintenance policy, maintenance cost, and reliability measures are reviewed. From every developed model, it can be inferred that railway track maintenance via ballastless has given more results than the ballasted track model. This review completely provides the methods adopted for tracking maintenance practices along with their constraints. Further, the review has also proposed a
maintenance model for Indian metro rail for future endeavors. From every reviewed analysis, it is notable that time plays a major important role in all systems. Therefore, in order to avoid a time-lapse in taking speedy action at the track segment which requires immediate attention, a new system that integrates the database cloud is planned to be introduced in future work for the betterment of the Indian Metro Rail System.

Data Availability

There are no separate data associated with this article.

Conflicts of Interest

The authors declare that there are no conflicts of interest in this study.

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References

[1] D. Prescott and J. Andrews, “Modelling Maintenance in Railway Infrastructure Management,” in Proceedings of the Annual Reliability and Maintainability Symposium, pp. 1–6, Orlando FL, USA, January 2013.
[2] C. Zhang, Y. Gao, L. Yang, Z. Gao, and J. Qi, “Joint optimization of train scheduling and maintenance planning in a railway network: a heuristic algorithm using Lagrangian relaxation,” Transportation Research Part B: Methodological, vol. 134, pp. 64–92, 2020.
[3] S. A. Kollo, A. Puskas, and G. Kollo, “Ballasted track versus ballastless track,” Key Engineering Materials, vol. 660, pp. 219–224, 2015.
[4] T. Liden, “Railway infrastructure maintenance - a survey of planning problems and conducted research,” Transportation Research Procedia, vol. 10, pp. 574–583, 2015.
[5] E. Gustavsson, “Scheduling tamping operations on railway tracks using mixed-integer linear programming,” EURO Journal on Transportation and Logistics, vol. 4, no. 1, pp. 97–112, 2015.
[6] E. Gustavsson, M. Patriksson, A. B. Stromberg, A. Wojciechowski, and M. Onnheim, “Preventive maintenance scheduling of multi-component systems with interval costs,” Computers & Industrial Engineering, vol. 76, pp. 390–400, 2014.
[7] M. Wen, R. Li, and K. B. Salling, “Optimization of preventive condition-based tamping for railway tracks,” European Journal of Operational Research, vol. 252, no. 2, pp. 455–465, 2016.
[8] C. Stenstrom, P. Norrbom, A. Parida, and U. Kumar, “Preventive and corrective maintenance–cost comparison and cost-benefit analysis,” Structure and Infrastructure Engineering, vol. 12, no. 4, pp. 603–517, 2016.
[9] Z. Zhu, Y. Xiang, M. Li, W. Zhu, and K. Schneider, “Preventive maintenance subject to equipment unavailability,” IEEE Transactions on Reliability, vol. 68, no. 3, pp. 1009–1020, 2019.
[10] T. P. Carvalho, F. A. Soares, R. Vita, R. D. P. Francisco, J. P. Basto, and S. G. S. Alcalá, “A systematic literature review of machine learning methods applied to predictive maintenance,” Computers & Industrial Engineering, vol. 137, Article ID 106024, 2019.
[11] Q. Wang, S. Bu, and Z. He, “Achieving predictive and proactive maintenance for high-speed railway power equipment with LSTM-RNN,” IEEE Transactions on Industrial Informatics, vol. 16, no. 10, pp. 6509–6517, 2020.
[12] N. Balac, T. Sipes, N. Wolter, K. Nunes, B. Sinkovits, and H. Karimabadi, “Large scale predictive analytics for real-time energy management,” in Proceedings of the IEEE international conference on big data, pp. 657–664, Silicon Valley, CA, USA, October 2013.
[13] S. M. Famurewa, M. Asplund, M. Rantatalo, A. Parida, and U. Kumar, “Maintenance analysis for continuous improvement of railway infrastructure performance,” Structure and Infrastructure Engineering, vol. 11, no. 7, pp. 957–969, 2015.
[14] S. Jovanovic, H. Guler, and B. Coko, “Track degradation analysis in the scope of railway infrastructure maintenance management systems,” Gradevinar, vol. 67, no. 3, pp. 247–258, 2015.
[15] R. Schenkendorf, J. C. Groos, and L. Johannes, IFAC-PapersOnLine, vol. 48, no. 21, pp. 964–969, 2015.
[16] E. Ruijters, D. Guck, M. Van Noort, and M. Stoelinga, “Reliability-centered maintenance of the electrically insulated railway joint via fault tree analysis: a practical experience report,” in Proceedings of the 46th Annual IEEE/IFIP International Conference on Dependable Systems and Networks, pp. 662–669, Toulouse, France, June 2016.
[17] Z. Su and B. D. Schutter, “Optimal scheduling of track maintenance activities for railway networks,” IFAC-PapersOnLine, vol. 51, no. 9, pp. 386–391, 2018.
[18] S. B. Singh, R. Suresha, and K. H. Sachidananda, “Reliability-centered maintenance used in metro railways,” Journal Européen des Systèmes Automatisés, vol. 53, no. 1, pp. 11–19, 2020.
[19] M. Bababeik, S. Zerguni, M. Farjad-Amin, N. Khademi, and M. Bagheri, “Developing a train timetable according to track maintenance plans: a stochastic optimization of buffer time schedules,” Transportation Research Procedia, vol. 37, pp. 27–34, 2019.
[20] F. Peng and Y. Ouyang, “Track maintenance production team scheduling in railroad networks,” Transportation Research Part B: Methodological, vol. 46, no. 10, pp. 1474–1488, 2012.
[21] S., S. Ahmad, N., K. Mandal, G. Chattopadhyay, and J. Powell, “Development of a unified railway track stability management tool to enhance track safety,” Proceedings of the Institution of Mechanical Engineers - Part F: Journal of Rail and Rapid Transit, vol. 227, no. 5, pp. 493–516, 2013.
[22] Z. Su, A. Jamshidi, A. Nunez, S. Baldi, and B. De Schutter, “Integrated condition-based track maintenance planning and crew scheduling of railway networks,” Transportation Research Part C: Emerging Technologies, vol. 105, pp. 359–384, 2019.
[23] S. Sharma, Y. Cai, Q. He, R. Mohammadi, and Z. Li, “Data driven optimization of railway maintenance for track geometry,” Transportation Research Part C: Emerging Technologies, vol. 90, pp. 34–58, 2018.
[24] J. Andrews, D. Prescott, and F. De Rozieres, “A stochastic model for railway track asset management,” Reliability Engineering & System Safety, vol. 130, pp. 76–84, 2014.
[25] P. Lautala and H. Pouryousef, “Sensitivity analysis of track maintenance strategies for the high-speed rail (HSR)
Advances in Materials Science and Engineering

services,” ASME/IEEE Joint Rail Conference, vol. 54594, pp. 141–150, 2011.

[26] J. Andrews, “A modelling approach to railway track asset management,” Proceedings of the Institution of Mechanical Engineers - Part F: Journal of Rail and Rapid Transit, vol. 227, no. 1, pp. 56–73, 2013.

[27] P. Xu, R. Liu, Q. Sun, and L. Jiang, “Dynamic-time-warping-based measurement data alignment model for condition-based railroad track maintenance,” IEEE Transactions on Intelligent Transportation Systems, vol. 16, no. 2, pp. 799–812, 2015.

[28] D. Wang, S. Zhan, Q. Peng, and W. Zhou, “Integrated overnight train scheduling and maintenance planning for high-speed railway lines,” Transportation Research Record, vol. 2675, no. 3, pp. 222–237, 2021.

[29] A. Consilvio, A. Di Febbraro, and N. Sacco, “A Modular Model to Schedule Predictive Railway Maintenance Operations,” in Proceedings of the 2015 International Conference on Models and Technologies for Intelligent Transportation Systems, pp. 426–433, Budapest, Hungary, June 2015.

[30] D. Prescott and J. Andrews, “Investigating railway track asset management using a Markov analysis,” Proceedings of the Institution of Mechanical Engineers - Part F: Journal of Rail and Rapid Transit, vol. 229, no. 4, pp. 402–416, 2015.

[31] T. Xin, S. M. Famurewa, L. Gao, U. Kumar, and Q. Zhang, “Grey-system-theory-based model for the prediction of track geometry quality,” Proceedings of the Institution of Mechanical Engineers - Part F: Journal of Rail and Rapid Transit, vol. 230, no. 7, pp. 1735–1744, 2016.

[32] M. Karimpour, L. Hitthamillage, N. Elkhoury, S. Moripdour, and R. Hesami, “Nonlinear Estimation Model for Rail Track Deterioration,” International Conference on Transportation Economics and Transportation Systems, vol. 11, no. 9, 2017.

[33] F. Pargar, O. Kauppila, and J. Kujala, “Integrated scheduling of preventive maintenance and renewal projects for multi-unit systems with grouping and balancing,” Computers & Industrial Engineering, vol. 110, pp. 43–58, 2017.

[34] R. Macedo, R. Benmansour, A. Artiba, N. Mladenovic, and D. Urosevic, “Scheduling preventive railway maintenance activities with resource constraints,” Electronic Notes in Discrete Mathematics, vol. 58, pp. 215–222, 2017.

[35] K. Argyropoulou, C. Ilipooulou, and K. Kepaptosgoulo, “Model for corrective maintenance scheduling of rail transit networks: application to Athens metro,” Journal of Infrastructure Systems, vol. 25, no. 1, Article ID 04018035, 2019.

[36] F. G. Pratico and M. Giunta, “An Integrative Approach RAMS-LCC to Support Decision on De-sign and Maintenance of Rail Track,” in Proceedings of the International Conference on Environmental Engineering. ICEE, Vilnius, Lithuania, April 2017.

[37] F. Sajedi and H. A. Razak, “Comparison of different methods for activation of ordinary Portland cement-slag mortars,” Construction and Building Materials, vol. 25, no. 1, pp. 30–38, 2011.

[38] C. Dao, R. Basten, and A. Hartmann, “Maintenance scheduling for railway tracks under limited possession time,” Journal of Transportation Engineering Part A: Systems, vol. 144, no. 8, Article ID 04018039, 2018.

[39] F. Peng and Y. Ouyang, “Optimal clustering of railroad track maintenance jobs,” Computer-Aided Civil and Infrastructure Engineering, vol. 29, no. 4, pp. 235–247, 2014.

[40] J. A. Braga and A. R. Andrade, “Optimizing maintenance decisions in railway wheelsets: a Markov decision process approach,” Proceedings of the Institution of Mechanical Engineers - Part O: Journal of Risk and Reliability, vol. 233, no. 2, pp. 285–300, 2019.

[41] L. C. B. Sanche, J. A. P. Braga, and A. R. Andrade, “Optimizing maintenance decision in rails: a Markov decision process approach,” ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, vol. 7, no. 1, Article ID 04020051, 2021.

[42] A. Lopez-Pita, P. F. Teixeira, C. Casas, A. Bachiller, and P. A. Ferreira, “Maintenance costs of high-speed lines in Europe state of the art,” Transportation Research Record, vol. 2043, no. 1, pp. 13–19, 2008.

[43] A. R. Andrade and P. F. Teixeira, “Hierarchical Bayesian modelling of rail track geometry degradation,” Proceedings of the Institution of Mechanical Engineers - Part F: Journal of Rail and Rapid Transit, vol. 227, no. 4, pp. 364–375, 2013.

[44] A. R. Andrade and P. F. Teixeira, “Statistical modelling of railway track geometry degradation using hierarchical Bayesian models,” Reliability Engineering & System Safety, vol. 142, pp. 169–183, 2015.

[45] A. R. Andrade and P. F. Teixeira, “Exploring different alert limit strategies in the maintenance of railway track geometry,” Journal of Transportation Engineering, vol. 142, no. 9, Article ID 04016037, 2016.

[46] O. Francois, L. Bouillaut, and S. Dubois, “A Multi-Nets Approach for Modeling and Evaluating Rail Maintenance Strategies,” in Proceedings of the 9th World Congress on Railway Research, pp. 22–26, France, May 2011.

[47] C. Vale and S. M. Lurdes, “Stochastic model for the geometrical rail track degradation process in the Portuguese railway Northern Line,” Reliability Engineering & System Safety, vol. 116, pp. 91–98, 2013.

[48] C. Vale and I. M. Ribeiro, “Railway condition-based maintenance model with stochastic deterioration,” Journal of Civil Engineering and Management, vol. 20, no. 5, pp. 686–692, 2014.

[49] Q. He, H. Li, D. Bhattacharya, D. P. Parikh, and A. Hampapur, “Railway track geometry defect modeling: deterioration, derailment risk and optimal repair,” in Proceedings of the Transportation Research Board Annual Meeting. The Academy of Transportation Research Board, Washington DC US, January 2013.

[50] Q. He, H. Li, D. Bhattacharya, D. P. Parikh, and A. Hampapur, “Track geometry defect rectification based on track deterioration modelling and derailment risk assessment,” Journal of the Operational Research Society, vol. 66, no. 3, pp. 392–404, 2015.

[51] M. Audley and J. D. Andrews, “The effects of tamping on railway track geometry degradation,” Proceedings of the Institution of Mechanical Engineers - Part F: Journal of Rail and Rapid Transit, vol. 227, no. 4, pp. 376–391, 2013.

[52] A. R. Andrade and P. F. Teixeira, “Unplanned-maintenance needs related to rail track geometry,” Proceedings of the Institution of Civil Engineers-Transport, vol. 167, no. 6, pp. 400–410, 2014.

[53] A. R. Andrade and P. F. Teixeira, “Biobjective optimization model for maintenance and renewal decisions related to rail track geometry,” Transportation Research Record, vol. 2261, no. 1, pp. 163–170, 2011.

[54] P. Xu, C. Jia, Y. Li, Q. Sun, and R. Liu, “Developing an Enhanced Short-Range railroad Track Condition Prediction Model for Optimal Maintenance Scheduling,” Mathematical Problems in Engineering, vol. 2015, Article ID 796171, 12 pages, 2015.
[55] P. C. Lopes Gerum, A. Altay, and M. Baykal-Gürsoy, “Data-driven predictive maintenance scheduling policies for railways,” *Transportation Research Part C: Emerging Technologies*, vol. 107, pp. 137–154, 2019.

[56] I. A. Khoury, P. O. Larsson-Kraik, A. Nissen, U. Juntti, and H. Schunnesson, “Optimisation of track geometry inspection interval,” *Proceedings of the Institution of Mechanical Engineers - Part F: Journal of Rail and Rapid Transit*, vol. 228, no. 5, pp. 546–556, 2014.

[57] A. Kasraei, J. A. Zakeri, and A. Bakhtiyari, “Optimal track geometry maintenance limits using machine learning: a case study,” *Proceedings of the Institution of Mechanical Engineers - Part F: Journal of Rail and Rapid Transit*, vol. 235, no. 7, pp. 876–886, 2021.

[58] H. Khajehei, A. Ahmadi, I. Soleimanmeigouni, and A. Nissen, “Allocation of effective maintenance limit for railway track geometry,” *Structure and Infrastructure Engineering*, vol. 15, no. 12, pp. 1597–1612, 2019.

[59] I. Soleimanmeigouni, A. Ahmadi, and U. Kumar, “Track geometry degradation and maintenance modelling: a review,” *Proceedings of the Institution of Mechanical Engineers - Part F: Journal of Rail and Rapid Transit*, vol. 232, no. 1, pp. 73–102, 2018.

[60] J. Neuhold, I. Vidovic, and S. Marschnig, “Preparing track geometry data for automated maintenance planning,” *Journal of Transportation Engineering, Part A: Systems*, vol. 146, no. 5, pp. 1–11, 2020.