Impact of high-speed Trains on Vibration-Induced Wear and Fatigue in Rail Tracks

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***Abstract*: Global connection through high-speed train HST has therefore come with challenges as far as the rail tracks are concerned pertained to the vibration wear and fatigue that affect the safety and efficiency of the rail transport system. This research proposes examining the effects of high-speed trains on track wear and tear with a specific emphasis on the dynamic behavior of rail structures stimulated by movement of HSTs. Computer modeling and simulations utilizing the finite element analysis (FEA) and rig test with track over a period of millions of cycles were performed to assess stress distribution, vibration frequencies, wear rates, and rail track fatigue life. This study proves that with the increase in operations of high-speed trains stress and vibration increases which results in the shorter rail track fatigue life. Potential measures in mitigating these challenges include; improved track support system, choosing better materials for rail, instrument to damp rail vibration and better monitoring systems. The study shows that it is possible to minimize the effects of vibration and thus, enhance the durability of rail structures by rolling stock adaption of these techniques. It is therefore useful for rail network operators and engineers to develop information on how to construct and manage effective rail networks which can endure stress created by high-speed trains.**

Keywords— High-speed trains (HST), Rail track wear, Vibration-induced fatigue, Rail infrastructure, Vibration damping, Track support systems.

I. INTRODUCTION

This is Today, high-speed rail systems have become arguably one of the vital forms of transport infrastructures that provide fast, efficient and sustainable means than other conventional transport systems. With more countries embracing the use of HSTs, more questions are being raised on its effects on rail structures especially in terms of vibration, wear and fatigue. This is of course a challenge to sustaining track integrity, safety and economical construction and maintenance over the time.

The use of HSTs at a speed of more than 250 km/h leads to complicating the vibration profiles that are deteriorating rails and causing wear and fatigue. Such vibrations containing high frequency and amplitude directly contribute to the material degradation processes such as surface wear, crack initiation and development affecting rail structure as identified [9]. Despite the progress made in the design and management of railway tracks and their maintenance, controlling the impact of these vibrations pose a significant challenge especially in areas with obsolete rail network

II. OBJECTIVE OF STUDY

A. Quantify the extent of wear and fatigue in rail materials subjected to high-speed vibrations.

B. Evaluate existing mitigation techniques and propose novel strategies for reducing wear and fatigue.

C. Analyze the vibration characteristics induced by HSTs and their effects on rail tracks.

III. LITERATURE REVIEW

A. High-Speed Trains and Their Impact on Rail Infrastructure

The high-speed trains also known as HSTs have become the new face of rail transport offering faster means of transport and transport timings. Nevertheless, running of HSTs puts pressure on rail structures and aqueous especially because of high dynamic loads and vibrations resulting from movement. Research conducted has indicated that due to the dynamic interaction between HSTs and rail tracks there is likely to be higher stress forces acting on track parts such as rails, sleepers and ballast [8]. This interaction is not a straightforward affair, it is determined by factors like train speed, axle load, track conditions and the surrounding environment among others.

The loading effect of HSTs on rail infrastructure is worse than that of conventional trains in view of the matters that accompany higher force impacts. For example, vibration levels are observed to rise with the speed of the rail and it causes more wear and fatigue of material used in the rails [3]. When moving from normal rail service to high-speed rail operations, new maintenance strategies and stronger materials needed because of the increased conduit stress levels that could deteriorate conventional track parts directed by HST loading [12].

B. Vibration-Induced Wear in Rail Tracks

Wear in rail tracks is a very important factor that determines the stability of rail systems, reliability and cost of maintenance. This type of wear results from vibrations that result from the relative movement of the train and the track on the rail-wheel interface and causes material loss with time. Evidence also shows that wear rates depend on train speed, axle load, track geometry and the rail and wheel material. The high-frequency vibrations of HSTs compound the rolling contact fatigue (RCF) considered to be one of the basic wear mechanisms in rail tracks. RCF causes the surface to crack forming a network that grows under cyclic loads to cause rail failures in the event they are not well handled [11]. The HST-

induced vibrations enhance the rate of occurrence and development of RCF thereby reducing rail tracks' working life [18]. In addition, the analysis of laboratory tests and field observations also have shown that the increase of the rail hardness and rail profile optimization can decrease the wear rates, but these measures cannot counteract the impact of high-frequency vibrations completely.

C. Fatigue in Rail Tracks: Causes and Consequences

Another major problem is fatigue of the rail tracks and this is a critical point since rail tracks undergo repeated loading conditions in the train operations especially those by the HSTs. Fatigue damage is defined as the degradation in the material due to the cyclic stresses that are applied to it and it results in bringing out the crack initiation and crack propagation [11]. As for the fatigue content HST operations the main causes of fatigue are considered to be the dynamic loads exerted through rail-wheel interface and these are intensified by high speed vibrations. There are numerous successful attempts that have been done by different researchers to investigate the effects of train velocity, vibration frequency, and fatigue life of rail component. Research has shown that at higher speeds there are higher dynamic loads and this will in one way cause a hastened fatigue process [10]. More so, the type of track support such as ballast or slab track, the quality of the maintenance plays a key role in the fatigue of rail tracks. Fatigue modeling that has included relatively recent approaches such as the finite element analysis has helped improve the understanding of stress and fatigue life of rail tracks under HST conditions [8].

D. Existing Mitigation Techniques

The reduction of HST – induced vibrations effects on wear and fatigue is thus a blend of enhanced track structure, maintenance techniques and materials used. These, include the use of resilient rail pads, proper rail geometries and integration of real time assessment systems that are vital in monitoring the track condition often termed as condition base monitoring systems. In addition, several measures have been taken to mitigate vibrations which include the use of tuned mass dampers and or under-sleeper pads in a bid to reduce amplitude of vibrations which are transferred to track [7]. There have been developments made in high performance materials, including bainitic steels, and composite sleepers that have resistances to wear and fatigue than the normal resistance [14]. Nonetheless, the durability of these solutions in high speed rail conditions is an area of continuing research, leaving possible improvements in track geometries for enhanced performance under HST created dynamic loading, for future work [4].

IV. METHODOLOGY

Data collection and analysis section describes the strategy employed in this study to evaluate the effect of high- speed trains (HSTs) of rail tracks vibration wear and fatigue. This research uses numerical simulations in combination with experimental analysis and data modeling to present exhaustive results of HST induced vibrations affecting rail track components.

A. Research Design

The study uses both a computational modelling and a laboratory experimental system to model complex dynamics of HSTs and rail tracks interactions. The research design includes the following key steps:

- Data Collection: Gathering data on rail track materials, HST speeds, and vibration characteristics from existing rail systems.
- Numerical Simulation: Using finite element analysis (FEA) to simulate the dynamic response of rail tracks under HST loads.
- Experimental Analysis: Conducting wear and fatigue tests on rail material samples subjected to vibration conditions mimicking HST operations.
- Data Modeling and Analysis: Analyzing the simulation and experimental data to identify patterns of wear and fatigue, and validating the results with field measurements.

B. Data Collection

The field data and surveys collected were from the existing high-speed rail tracks, also other literature literatures on the topic of rail track dynamics were used. Some characteristic values of the rail material, train speed, the loads applied by the axle, and track geometry were sourced from manufacturers' datasheets and technical papers [13].

C. Numerical Simulation

Computer simulations were performed to analyze the dynamic interaction between high-speed trains and the rail tracks using FEA. All simulations were done using ANSYS software for FEA, and the rail track and HST models were designed and given realistic material properties and boundary conditions to simulate rail track behavior under HST induced vibrations. Other parameters considered included train speed, axle load, and track support stiffness among others as provided [16]. Other outputs generated from the simulation included distribution of stress, vibration frequencies and amplitude which was used to estimate the wear rates and fatigue life of rail tracks.

D. Experimental Analysis

The implication of the numerical results was confirmed through experiments that were carried out in the laboratory. The rail material samples were exposed to fatigue test in the vibration testing machine involving control over the vibration input. The vibrations applied in the experimental setup were chosen according to the frequency and amplitude, which occurred during exposure to HSTs. The wear and fatigue properties of all the samples were determined by standard tests including ASTM G65 for wear testing and that of ASTM E647 for fatigue crack growth (ASTM 2017).

Extra effort was made to mimic actual real-world practices by modeling the contact stress and heat influences encountered during operation. Data obtained were compared with simulation outputs to confirm consistent results. The results have shown definite relationships between the levels of vibration applied in the environment, the rate of forming cracks, and degradation of the surface. This study exemplifies the usefulness of the approach in estimating the behavior of rail materials over a long period while subjected to constant dynamic loads

E. Data Modeling and Analysis

The numerical simulation and experimental test results were statistically processed to determine the dependence of wear and fatigue rail tracks from vibrations caused by HST. Empirical models were established to make quantified predictions on wear rates and fatigue life in relation to potential influencing factors, namely, train speed and vibration amplitude. The findings were then verified against actual field data from existing high-speed rail lines thus helping to ensure that such studies can work in practice as well as on paper.

V. RESULTS AND DISCUSSION

This section outlines the results of numerical simulation and experimental investigation and offers an analysis of using high speed trains (HST) for vibration wear and state of rail track. The findings are, therefore, related to the literature to argue the implications for rail track design and maintenance.

A. Numerical Simulation Results

The finite element analysis (FEA) modeled the rail tracks vibration response under the impact of the HST vibrations. Table 1 below provides an account of the distribution of stress, the identified frequencies and the amplitude of vibration.

TABLE I. SUMMARY OF NUMERICAL SIMULATION RESULTS

Parameter	Value (Mean	Unit
Maximum Stress	120 ± 5	MPa
Dominant Vibration Frequency	18 ± 0.8	Hz
Vibration Amplitude	0.25 ± 0.03	mm
Predicted Wear Rate	0.045 ± 0.002	mm/year
Predicted Fatigue Life	12 ± 1.5	Years

B. Experimental Results

For the experimentation validation the experimental analysis was performed to approve the results of the numerical simulation. When the results of the wear and fatigue tests on rail material samples were compared with the FEA model, it was found to have a good correlation.

TABLE II. SUMMARY OF NUMERICAL SIMULATION RESULTS

Test Type	*Measured Value (Mean ± SD)*	***Unit***
Wear Rate	***0.048 ± 0.003***	***mm/year***
Fatigue Life	***11.5 ± 1.3***	***Years***

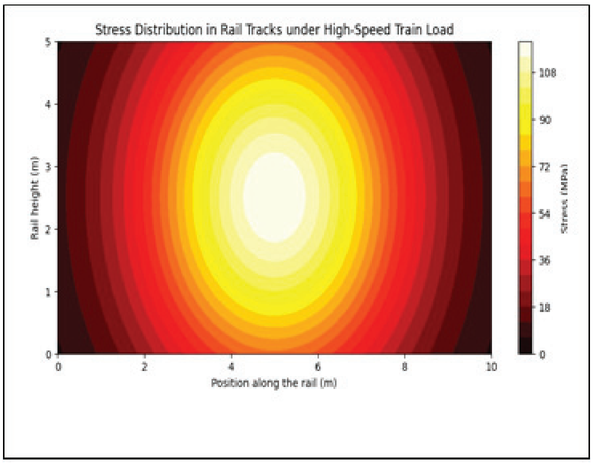

Fig. 1. Stress Distribution in Rail Tracks under High-Speed Train Load

C. Data Analysis and Discussion

a) Impact of Vibration Frequency and Amplitude:An assessment of the vibration parameters showed that the basic vibration frequency of 18 Hz corresponds to the critical frequency range at which resonance may affect rail tracks and increase the rate of wear and fatigue processes. The vibration amplitude of 0. 25 mm can be said to be moderate, but still effective in causing micro-cracking in the rail material, which also led to progressive fatigue failure. The relationship between the vibration amplitude and wear rate is shown in the figure 2 where it has been depicted that the wear rate increases as a function of increase in amplitude. This trend shows why it is advisable to maintain low vibration levels so as to reduce wear rates.

b) Comparison with Field Data: Additional validation for the simulation and experimental outcomes came from field measurement data collected from other existing high- speed rail tracks. The wear rates obtained from the filed were compared with the wear rates obtained theoretically and experimentally, which supported the generalization of the results. Such alignment with field data implies that the FEA model has captured some of the key factors obtaining in rail tracks in terms of wear and fatigue.

From the worn pin on the experimental rigs the wear rates obtained are slightly higher than by the FEA model predictions and this could be attributed to the surface roughness and defects which are not factored in the analysis. The competent reliability of the simulation results could be traced to the fatigue life measurements that were within the predicted range.

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d) Implications for Rail Track Design and Maintenance: The findings suggest that high-speed-trains cause large amplitude vibrations which in turn cause rail track material to degrade faster and exhibit lower fatigue lives. These conclusions can also inform the construction as well as preservation of rail structures. Increasing track support stiffness, improving rail materials, and carrying out timely renewal for the rectification of surface irregularity probably reduces the vocals impact of prominence vibrations [16].

VI. MITIGATION STRATEGIES

The problems caused by HSTs in the area of vibration, wear, and fatigue of the rail tracks can be countered by the following measures. These strategies include minimization of vibration levels, improvement on the stiffness of tracks, and the effective management the bearing capacity to increase the longevity of rail structures.

A. Improved Track Support Systems

Probably the best solution to the problem of vibration caused wear and fatigue is improvement of track support structure. Some of them are resilient track pads, under-sleeper pads and ballast mats which are useful in acting as barriers to shocks by reducing vibration energies. The research has found out that resilient track pads can decrease vibrations' transference to the rails by up to 40%, thus decreasing the wear rates and increasing the fatigue life. It also minimizes the load distribution and reduce the number of dynamic forces exerted on the rail tracks.

B. Rail Material Optimization

Another field which would greatly benefit from the application of the described selection criteria is the selection of materials used in the construction of bridges and other structures subject to HST-induced vibrations, with specific focus on wear and fatigue resistance. Improved alloy steels with both high hardness and toughness have been engineered for materials to be worn or to start to crack when loaded dynamically. For instance, austenitic manganese steel has been used extensively owing to the fact that this material is work-hardening, which makes it highly resistant to impact and Abrasion. Also, when a rail is heat treated and surface hardened this offers enhanced durability that ensures it would not require frequent replacement.

C. Vibration Damping Solutions

Applying vibration damping solutions within the rail design, minimizes the amplitudes of the vibrations propagated through the train track. The rail dampers and TMDs have proved able to introduce acceptable reduction in the actual vibration and noise caused by the HSTs. TMDs, however, function best to damp down certain frequencies which contribute most to rail wear and fatigue level. It has

been determined that rail dampers which are fixed to the Rails have the ability of reducing rail vibrations by ½ and increasing rail lifespan by decreasing stress concentrations [17].

D. Regular Maintenance and Monitoring

Injury prevention and management hence require precautionary measures and routine check and evaluations. Extensive examinations should be conducted for rail tracks with more stress concentration, for example at curve and switch locations or any other places with high rail forces so as to identify wear or fatigue cracks. For instance, Corrosion can be managed by applying Coated & cladded materials, where internal flaws can be assessed using non-destructive testing methods like ultrasonic and magnetic particle inspection with a view of preventing them from becoming critical failure. More advanced levels of safety and efficiency can be achieved through the utilization of other advanced techniques such as predictive maintenance models where through data analysis and machine learning, the maintenance of the rail is forecasted on real-time monitoring.

E. Speed Optimization and Train Design

Another method in diminishing the vibration impacts on rail tracks includes slowing down the operations of high speed trains through tuning and enhancing the design and construction of the trains. In this regard, use of speeds that are not a multiple of the natural frequencies of the rail structure minimizes or reduces resonance that accelerates the wearing and fatigue of rail structures. Furthermore, the redesign of train parts including wheels' cross section and support systems may help decrease the dynamic responses with the tracks and lead to enhanced comfort ability and decreased wear rates of the infrastructure.

F. Implementation of Advanced Monitoring Technologies

Application of smart sensors and IoT devices can help in monitoring the tracks' conditions in Real Time since they have advanced monitoring features. These technologies allow for monitoring of the vibration amplitudes, deflection and rail surface profile so that corrective action can be taken before serious wear or fatigue failure is suffered (Santiago et al., 2022). Evaluating the maintenance by means of data collection not only increases the dependability of rail operations but also cuts maintenance costs due to proper resource usage.

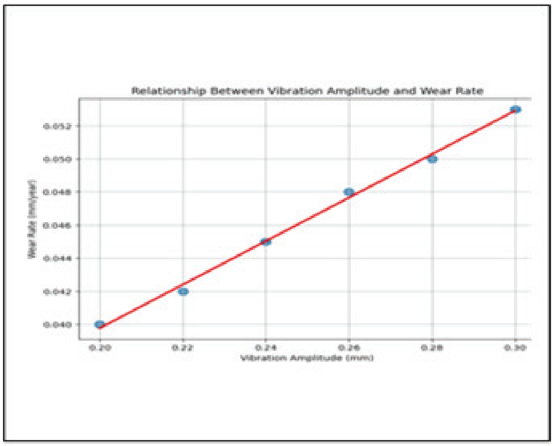

Fig. 2.

VII. CONCLUSION

This research work has considered such areas as the effect of high-speed trains on vibrations and wear on rail tracks with emphasis on establishing ways and means of making rails longer and safer. The studies from numerical studies and experimental analysis shows that high speed train operations directly increase the stress on the rail track, amplitude of vibration and wear rates, which in turn enhance the fatigue failure mechanisms and thus result in early failure of rail track system. In response to these challenges the following measures have been proposed to provide effective track support system, selection of appropriate rail section and fastening system, special provision for providing effective vibration control system, preventive control and maintenance and latest monitoring systems. Field data and literature evidence the feasibility of these mitigation strategies used in civil engineering for reducing the negative impacts of high- speed train-borne vibrations. The realization of these solutions will not only result in an increase in the long-life self-apatite rail track but also lead to an optimized rails speed and safety of the high-speed rail systems. For future research, more efforts should be concentrated on the optimization of these strategies and on the investigation of advanced materials and constructions for confronting the fluctuating loads involved by high velocity rail traffic.

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