Journal of Ethiopian Association of Civil Engineers (EACE Journal)
Vol.15, Issue 1 (2024)
www.eacecivil.org | ISSN 3005-6446 (Print)

Dynamic Behaviour of Prestressed Concrete Railway Bridges with Track Irregularities: Case Study on Addis Ababa–Djibouti Railway Line

Abrham Gebre Tarekegn
School of Civil and Environmental Engineering, Addis Ababa Institute of Technology, Addis Ababa University, Addis Ababa, Ethiopia
E-mail address: abrham.gebre@aait.edu.et

Abstract

Track irregularities, a significant excitation mechanism in the track-vehicle dynamic system, should be minimized to ensure that traffic on a railway line operates safely. To minimize such a problem, proper alignment of tracks in vertical and lateral directions is required. In line with this, the vibration of the vehicle-bridge coupling is a complex process, including the vehicles' multi-body dynamics, the bridges' structural dynamics, and the wheel-rail contact interactions. The likelihood of trains operating across bridges during uncertain parameters is significantly increased by their frequent use. The novel model allows the simultaneous input of several excitations with multi-coupling effects, such as random loads from vehicles, random track irregularities, and significant lateral wind forces. In this study, a novel technique known as "multi-body dynamics integrated with uncertainty parameters (MBD-UP)" was developed, and the bridge substructure and slab track were generated using the finite element method. Field measurement data from a 21-meter prestressed concrete (PC) railway bridge is used for verification. In this study, effects of uncertainties in track irregularity, wind speed, train speed and others on performance of a PC railway bridge in the Addis Ababa - Djibouti Railway Line is investigated. Results showed that the bridge received more significant vertical and lateral accelerations due to track irregularities and as speed exceeds 70 km/hr, the bridge's performance is affected. Frequent inspection and maintenance of tracks are recommended to enable the train to operate at design speed.

Keywords: Vehicle-Bridge Coupling, MBD-UP, Vibration, PC Railway Bridge, Uncertainties, Track Irregularity

1. Introduction

Track irregularities are deviations from the intended track geometry. A track is of high quality if it closely adheres to the selected track geometry and has only minor track imperfections. Track irregularities are often considered to be deviations from design geometry within a range of 1 to 200 m in wavelength (Karis, 2018). Track irregularities (uneven settlement, misalignment, or abrupt transitions) can induce dynamic loading on the bridge structure. This track irregularities impact prestressed concrete railway bridges by introducing dynamic loading, resonance effects, dynamic amplification, and affecting the performance of structural elements such as bearings and joints (Malveiro et al., 2018). The dynamic issues in a train-bridge coupled system, particularly the operating safety concern of trains crossing a bridge under the effect of many random elements, have drawn more attention. Bridges are increasingly being used as the supporting structures for railways since these railways must adhere to significantly tighter design criteria than ordinary railways to guarantee their trains' safety and stability.

Many researchers have studied the interaction dynamics of train-track/bridge systems (Antolín et al., 2013; Li et al., 2015; Lou et al., 2012; Mao et al., 2016; Yu et al., 2016; Zeng et al., 2016). Nonetheless, most previous studies on dynamic analysis in a train-bridge coupled system employed the time-varying deterministic dynamic analysis method. The conventional deterministic dynamic model was unable to account for the randomness of the train-bridge coupled vibration. Track irregularities and their random nature are widely recognized (Lei & Noda, 2002; Lei & Zhang, 2011). It is necessary to apply random vibration theory to understand the dynamic responses of the train–track/bridge interaction system. The Monte Carlo method has been used in most prior literature (Au et al., 2002; Xia & Zhang, 2005), to create time history sample functions of random track irregularities. Based on these dynamic responses, the system's random vibration properties were then determined through statistical process. The interaction model, in the context of vehicles and bridges (Garg, 2012), incorporates track imperfections as a significant excitation source. The data used to study this phenomenon may originate from physically measured track profiles (Xia et al., 2003; Zhang et al., 2008; Zhang et al., 2010). Alternatively, random profiles could be produced using power spectral density functions (Claus & Schiehlen, 1998; Du Kim & Warnitchai, 2009; Nguyen et al., 2009). The Dynamic response of railway bridges under heavy-haul freight trains considering different random variables was studied by (Xiao et al., 2020). In the analysis, a heavy-haul freight train with 2 systems was carried out by considering a train-track-bridge dynamic coupling system. In this case, different random variables of the C80 freight car were used. Some of the parameters used in the study are the car’s mass, vertical and lateral stiffnesses of primary and secondary suspensions, vertical and lateral damping of primary and secondary suspensions and so on (Majka & Hartnett, 2009).

Research studies on railway dynamic analysis have contributed significantly to the field. However, the train-bridge coupled system's random dynamic properties were identified with enough accuracy. In such cases, it is essential to consider the coupling influence of different parameters while evaluating a fully flexible vehicle model, and this study takes these conditions into account and actual track irregularity data. According to (Gao et al., 2020), a coupled vehicle-bridge model was created using ANSYS and SIMPACK. A 3D model of the bridge was constructed in ANSYS using

finite element techniques. Su et al. (2010) developed a numerical vibration prediction scheme for train-bridge systems using MATLAB and FE software ABAQUS. The integration of equations of motion was carried out using a train-bridge interaction system designed by the researcher (Liu et al., 2009). The train model had 27 degrees of freedom (DOFs), while the railway bridge model was a finite element (FE) model. Olmos & Astiz (2013) studied the lateral reactions of viaducts by developing a finite element model of high pier viaducts and the vehicle-bridge interaction study. (Lee et al., 2006) finite element modal analysis of the bridge and Lagrange's formulation for monorail trains were utilized to examine the dynamic responses of a monorail steel bridge.

In a previous study, Lei and Noda (2002) investigated primarily on the effect of vertical track irregularity. However, the impact of combined effect of wind speed, train speed, passenger weight, and track irregularities is not addressed. Thus, in this work, a coupled vehicle-bridge model is created using SIMPACK and ANSYS considering different combinations of random variables. The model is based on multi-body dynamics and finite element methods. A 3D bridge model was generated in ANSYS and a vehicle model with 35 degrees of freedom (DoF) was created in SIMPACK using approaches similar to those investigated by Momhur et al. (2021) and Bigoni et al. (2014). The use of a vehicle model with 35 DoF is important because it gives a thorough and accurate representation of vehicle dynamics, captures complex interactions between the vehicle and the bridge, and assures realistic load transfer to the structure.

The MBD-UP approach effectively integrates FEM and MBD to model the bridge structure and simulate the train's dynamic interaction with the bridge. Uncertainty parameters are incorporated into the MBD simulation to enhance the accuracy of the dynamic response predictions (El-Ghandour and Foster, 2019). This method provides a solid basis for studying the dynamic performance of railway bridges under different operational and environmental conditions. The results of this study showed that when vehicle speed increased with high uncertainty of track irregularity, the induced vibration of the bridge became significant, particularly for trains' speed exceeding 70 km/hr.

2. Materials and Methods

A new random three-dimensional connected train-track-bridge system is created using a coupling system. The substructure of the slab track and bridge is modelled using the finite element approach which takes into account bridge body's elasticity. Multi-body system dynamics are then introduced, considering random elements such as passenger weight changes, considerable lateral wind force, and track irregularity.

The workflow for the current study involves four main steps. First, a multi-body system dynamic of six connected vehicle models was created. Second, ANSYS's finite element method with a flexible three-dimensional slab track-bridge interaction model was used. Third, excitation related to track irregularities and rail is established using MATLAB. Fourth, randomly generated system parameters were used to simulate the system using the Monte Carlo simulation approach. Finally, the system dynamic, finite substructure output, random parameters, and track irregularity are coupled in SIMPACK software. Figure 1 presents the specific workflow for the current study.

2.1. Random Dynamic Model

Several random variables including wind force, passenger weight, and irregular track geometry affect the intricate and dynamic process of the train's contact with the track.

The numerical framework for the random train/track and bridge model is based on a 3D random vehicle model and a track stochastic with random wheel/rail interaction (Momhur et al., 2021).

2.1.1 Vehicle Model

Six degrees of freedom (DOFs) are represented by the longitudinal and vertical displacements of the train as recommended by (Li et al., 2015). It is also considered that the train has twelve bogies and six vehicle bodies. The centers of two successive cars are separated by 26 meters (Youcef et al., 2013).

2.1.2. General Equation of Motion

This study includes the general vehicle model's (Momhur et al., 2021) and dynamic equations, which consists of the vehicle's random properties and track irregularities generated by the track spectrum and the governed equation of motion is presented in Eqn. (1) (Youcef et al., 2013).

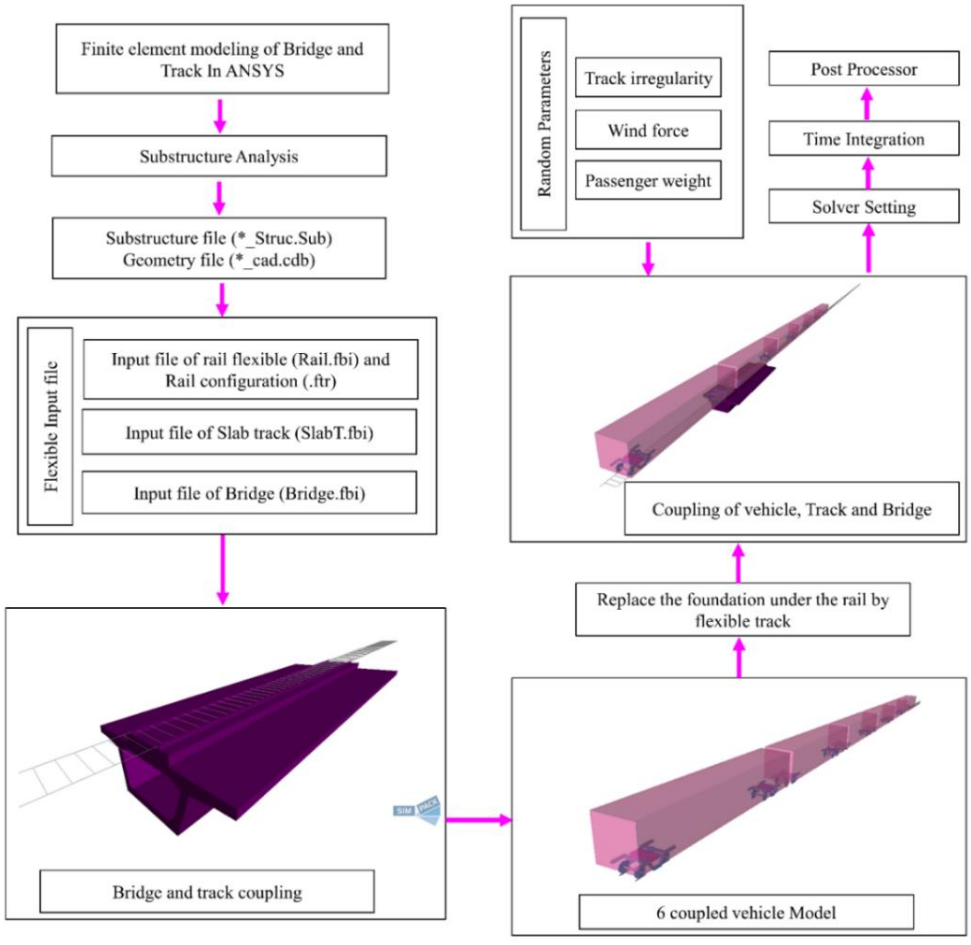


Figure 1 Flow Chart of Train-Track-Bridge Coupling Model

$$\begin{bmatrix} M_v & 0 & 0 & 0 \\ 0 & M_r & 0 & 0 \\ 0 & 0 & M_{sl} & 0 \\ 0 & 0 & 0 & M_{Br} \end{bmatrix} \begin{Bmatrix} \ddot{X}_v \\ \ddot{X}_r \\ \ddot{X}_{sl} \\ \ddot{X}_{Br} \end{Bmatrix} + \begin{bmatrix} C_v & C_{vr} & 0 & 0 \\ C_{rv} & C_r & C_{rsl} & 0 \\ 0 & C_{slr} & C_{sl} & C_{sBr} \\ 0 & 0 & C_{Brs} & C_{Br} \end{bmatrix} \begin{Bmatrix} \dot{X}_v \\ \dot{X}_r \\ \dot{X}_{sl} \\ \dot{X}_{Br} \end{Bmatrix} + \begin{bmatrix} K_v & K_{vr} & 0 & 0 \\ K_{rv} & K_r & K_{rsl} & 0 \\ 0 & K_{slr} & K_{sl} & K_{sBr} \\ 0 & 0 & K_{Brs} & K_{Br} \end{bmatrix} \begin{Bmatrix} X_v \\ X_r \\ X_{sl} \\ X_{Br} \end{Bmatrix} = \begin{Bmatrix} F_v \\ F_r \\ F_{sl} \\ F_{Br} \end{Bmatrix} \quad \text{(Eqn. 1)}$$

Where *M*, *C* and *K* represent the mass, damping and stiffness sub-matrices, *X* and *F* denote the displacement and force sub-vectors respectively, and the subscripts '*v*', '*r*', '*sl*' and '*Br*' designate vehicle, rail, slab and bridge, respectively.

2.1.3. Wheel/Rrail Interaction Model

The wheel/rail interaction model is crucial in the vehicle-track coupled system. Figure 2 illustrates the wheel/rail interaction model and the rail force vector. To address the wheel/rail contact geometry relation, the wheel/rail contact geometry model proposed by (Chen & Zhai, 2004) is employed with the track vibration, namely the rail motions. This allows the wheel force vector equation to be formulated. Table 1 provides a detailed presentation of the CRH3 specifications used for validation.

Table 1 Parameters of CRH3 (Zhai et al., 2009)

Parameters	Notation	Unit	Value
Mass of car body	M_c	kg	40000
Mass of bogie	M_t	kg	3200
Mass of wheel	M_w	kg	1200
Pitch inertia of car body	J_c	kg·m^2	5.47×10^5
Pitch inertia of bogie)	J_t	kg·m^2	6800
Stiffness of the primary suspension system	K_p	MN/m	2.08
Stiffness of the secondary suspension system	K_s	MN/m	0.8
Damping of the primary suspension system	C_p	kN·s/m	100
Damping of the secondary suspension system	C_s	kN·s/m	120
Wheelbase 2 (m)	m	m	2.5
Distance between bogie centres	m	m	17.375
Length of vehicle (m)	m	m	25.675
Stiffness of wheel/rail contact	K_c	MN/m	1.325 ×10^3
Axle load	P	kN	140

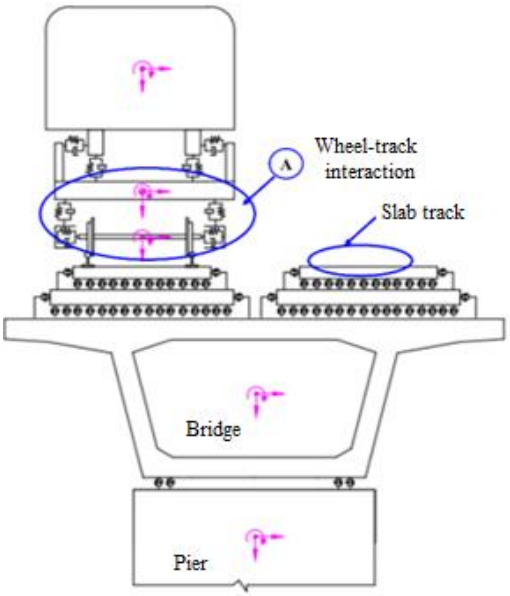


Figure 2 Model of Random Train-Track-Bridge with Interaction between Wheels and Rails

2.1.4. Track and Bridge Model

In track and bridge modelling, the following assumptions are used.

i) A flexible body model is used
ii) Rails are deformable: in simulations of multi-body rail dynamics utilizing a floating reference frame of design, as illustrated in (Shabana, 2020).
iii) Rail distortion is evident beneath each wheel of the floating track frame
iv) Irregularity in tracks geometry exists (Frýba, 1996).

The lateral and vertical track irregularities are computed using Eqn. (2) (Frýba, 1996) and the time-frequency technique. Then, the track geometry is transformed both horizontally and vertically from Power Spectral Density (PSD).

$$S(f) = \frac{A(f^2 + Bf + C)}{f^4 + Df^3 + Ff + G} \qquad \text{(Eqn. 2)}$$

where:

A to *G* : specific parameters of the irregular nature of the track (Frýba, 1996)

f : frequency (Hz)

S(*f*) : track-rail spectrum function

The track rail spectrum data given in Table 2, slab track, bridge girder and pier data shown in Table 3 were used for model validation.

Table 2 Parameters Value for Track Rail Spectrum (Zhai et al., 2009)

Parameters	A	B	C	D	E	F	G
Left rail vertical (LV)	0.1271	-2.1531	1.5503	4.9835	1.3891	-0.0327	0.0018
Right rail vertical (RV)	0.3326	-1.3757	0.5497	2.4907	0.4057	0.0858	-0.0014
Left rail lateral (LL)	0.0627	-1.1840	0.6773	2.1237	-0.0847	0.0342	-0.0005
Right rail lateral (RL)	0.1595	-1.3853	0.6671	2.3331	0.2561	0.0928	-0.0016

Table 3 Significant Parameters of Slab Track and Bridge (Zeng et al., 2015)

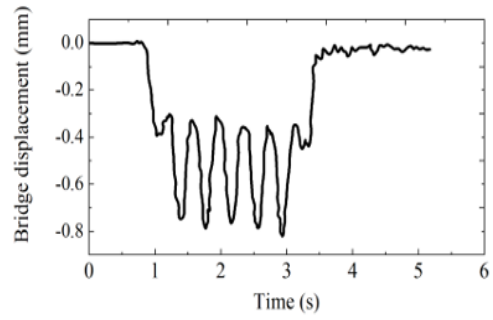
Item	Notation	Unit	Mean value
Slab track			
Mass per unit length of rail	m_r	kg/m	60.64
Flexural moment of inertia about the y-axis of the cross-section of the rail	I_{ry}	m^4	3.22×10^5
Flexural moment of inertia about the z-axis of the cross-section of the rail	I_{rz}	m^4	5.24×10^6
Mass per unit length of slab	m_s	kg/m	1.2×10^3
Flexural moment of inertia about the y-axis of the cross-section of the slab	I_{sy}	m^4	1.4×10^3
Flexural moment of inertia about the z-axis of the cross-section of the slab	I_{sz}	m^4	0.22
Lateral stiffness of fastener	k_{rsy}	N/m	3.0×10^7
Vertical stiffness of fastener	k_{rsz}	N/m	5.0×10^7
Bridge girder and pier			
Fundamental frequency of girder (vertical)	f_{b1}	H_z	1.23
Mass per unit length of the pier	m_p	kg/m	1.86×10^5
Flexural moment of inertia about the x-axis of the cross-section of the pier	I_{px}	m^4	1.41×0^3

2.2. Model Validation

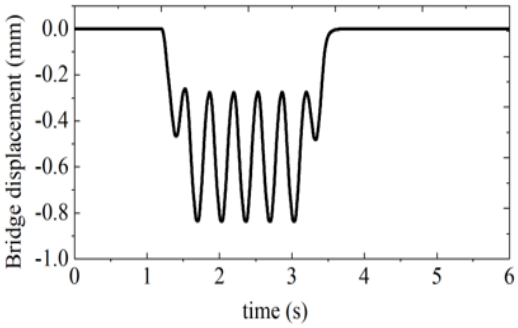
Parameters given in Tables 1 to 3 are used as input variables and a finite element model of the railway bridge was modeled. In the simulation, train speeds were set at 270 km/hr to account the site measurement of the actual speed data. Numerical simulation was carried out at the selected intervals of traveling distance. Field- measured values data of a 21-meter PC railway bridge (Youcef et al., 2013) were used to compare the displacement responses at the mid-span of the bridge. The outputs of the numerical model and field measurement results shown

in Figure 3 are similar but there are some limitations which can lead to biases in model validation results. Limited field measurement data in quantity, errors in field measurements and uncertainties in model parameters can affect the accuracy of the validation process (Lee et al., 2019).

In the numerical modeling of the current study, the bridge stiffness was adjusted to account for the identified bridge frequencies based on field measurement and the model was calibrated accordingly.



(a)



(b)

Figure 3 Bridge's Vertical Displacement a) Field Measurement (Youcef et al., 2013) and b) Simulation Result

2.3. Study Parameters

In this study, bridges along the Addis Ababa–Djibouti Railway (ADR) line is considered. ADR stretches from Sebeta to the Port of Doraleh. The route has a total length of 759 km of which 3% of the railway's total length are viaducts and bridges. Among this, the Sebeta to Adama line is the only double-track section of the line. It is a Chinese Class 2 standard-gauge (1435 mm) and the rail weighs 50 kg/m for all of its railways. The target speed for passenger's train is 120 km/hr (ARCE, 2021; Mengistu and G. Henok, 2021). The dynamic behavior of PC railway bridges with track irregularities involves multiple parameters. The parameters are discussed in the following sub-sections. The schematic diagram of the ADR line and bridge picture in the route are shown in Figures 4 and 5, respectively.

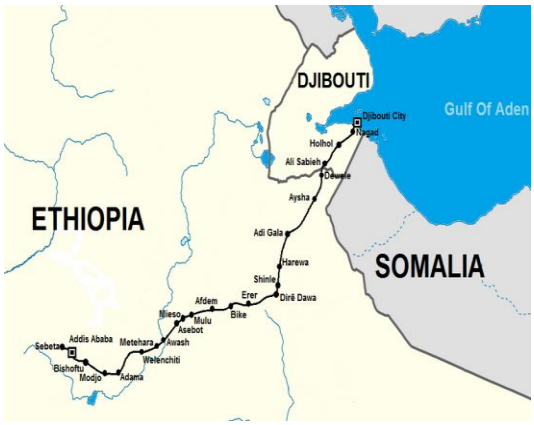


Figure 4 Schematic Diagram of ADR Line



Figure 5 Bridges on ADR Line (BRI, 2023)

2.3.1. Bridge Geometry & Materials Data

The bridge considered in this study is a PC bridge, which has a span of 24.5 m and is simply-supported. The typical cross-section of a prestressed concrete girder railway

bridge (ballastless/ slab track systems) with tendon arrangements at the end and mid-span of the bridge are shown in Figure 6 (ARCE, 2021).

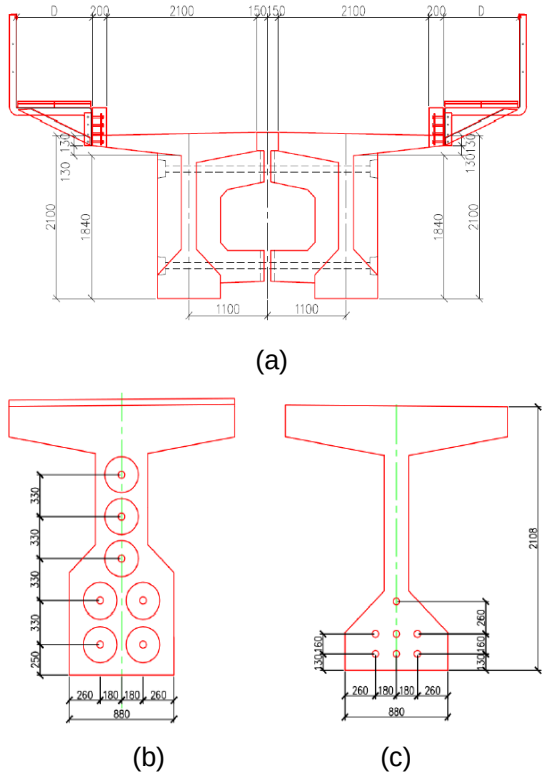


Figure 6 a) Cross-section of a Single-Track Bridge b) Tendon Arrangement at the End and c) Tendon Arrangement at the Mid-Span

The material properties of reinforcement bars, concrete, and prestressing tendons are shown in Table 4 (ARCE, 2021).

Table 4 Material Properties

Materials		Remarks
Concrete grade		C55
Rebars	HPB235	yield strength 235 MPa
	HRB 335	yield strength 335 MPa
Prestress tendons	Nominal diameter	15.2 mm
	Elongation	7.5%
	Prestressing force	< 260 kN
	f_{yp}, low-relaxation	1860 MPa
Rail	Class 2 standard-gauge (UIC50)	50 kg/m f_y=1190 MPa

2.3.2. Loading Condition

The train has six bodies with a total length of 144 m, and the cars are separated by 6.1 m (ARCE, 2021). As reported by (Chen, 2021), the current operational speed of the train is 55km/hr. In this study, the train's speed is considered to be between 60 km/hr and 120 km/hr. The loading configuration of each passenger coach is shown in Figure 7. In this study, axle load configuration is considered as random variables as the axle loads move across the bridge, the dynamic impact varies depending on the load magnitude, speed, and configuration (Fafard et al., 1997).

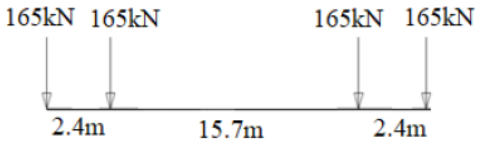
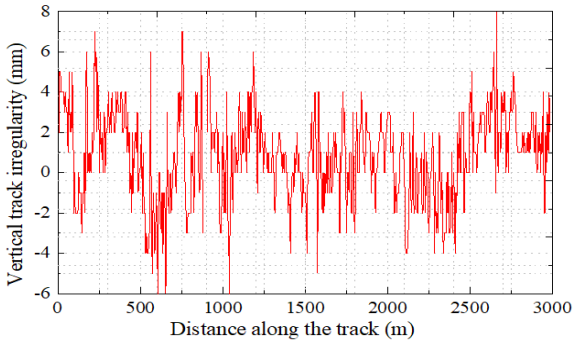


Figure 7 Axle Load Configuration of Passenger Coach (ARCE, 2021)

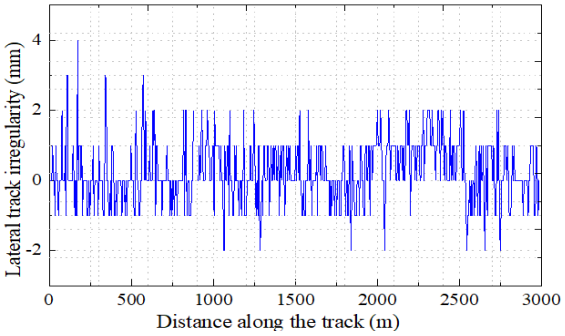
2.3.3. Track Irregularity Data

Track irregularities lead to fluctuating dynamic forces as trains pass over a bridge. In this regard, actual data on track irregularity was collected over a length of 3000m, analyzed and the results are plotted in Figure 8. Track irregularity data were collected using a gauge sensor installed on the inspection vehicle. Field investigation on the track deflection (Figure 9) under wheel load showed that the measured vertical and horizontal deflections due to wheel load; i.e, 0.7 mm and 0.3 mm do not exceed the limit of 6.35 mm and 3.18 mm specified in the manual, respectively (AREMA, 2010).

Suspension parameters with a coefficient of friction of 0.4 have been used as shown in Table 5 (Majka & Hartnett, 2009; ARCE, 2021). In addition, the statistical distribution of random variables considered in this study is shown in Table 6.



(a)



(b)

Figure 8 Track Irregularity Spectrum a) Vertical and b) Lateral



Figure 9 Field Measurement on Track Deflection

Table 5 Suspension Parameters

Properties	Directions		
	x	y	z
Primary spring stiffness, kN/m^2 (E+02)	7	70	8
Primary damping, kNS/m (E+02)	1.53	1.53	1.53
Secondary spring stiffness, kN/m^2 (E+04)	-	1.65	27.2
Secondary damper, kNS/m (E+03)	0.0014	4	8

Table 6 Random Variables

No.	Random variables	Min. value	Max. value	Ref.
1	Wind speed (km/hr)	4.5	14.9	(Weather & Climate)
2	Train speed (km/hr)	60	120	(Chen, 2021; ARCE, 2021)
3	Passenger's weight (Axle loads, ton)	12	17	(ARCE, 2021)
	Track irregularity (mm)			
4	Vertical	-5	5	Collected data
5	Lateral	-2	3	

To generate the possible combinations of random variables, the Latin Hypercube Sampling (LHS) method is used (Rücker et al., 2006). For such a task, a MATLAB built-in tool for LHS design with minimum and maximum criteria is utilized.

According to Yang et al. (2019), a log-normal distribution was used to generate random variables for wind and train speeds, while a normal distribution was used to others. The incorporation of uncertainty parameters in the model improved the accuracy of dynamic response predictions by accounting for variability in the actual conditions that can influence the performance of a railway bridge under dynamic loading as studied by Feng, D. and Feng, M. (2015). Thus, the number of combinations is computed using Eqn. (3) (Bursztyn and Steinberg, 2002):

$$n = 2^{p-q} \qquad \text{(Eqn. 3)}$$

where:

n : number of combinations
p : number of random variables
q = 2 (two-level factorial design)

For the 5 random variables and a two-level factorial design, a total of 8 combinations are generated (=2^{5-2}), as shown in Table 7 (NC denotes the bridge's normal condition which

includes a minimum train speed, nominal axle load and no track irregularities).

Table 7 Combinations of Random Variables

Cases	Wind speed (km/hr)	Train speed (km/hr)	Axle loads (ton)	Track irregularity (mm)	
				Ver-tical	Late-ral
NC	10	60	16.5	-	-
1	7.3	100	14.8	4.9	1.2
2	11.6	90	13.0	1.7	-1.8
3	14.7	80	15.4	-4.5	-0.2
4	10.1	85	12.1	-3.2	0.2
5	12.8	70	13.4	0.2	0.6
6	4.8	110	12.2	-2.5	2.4
7	8.6	115	16.2	-0.9	2.2
8	5.8	120	16.6	3.0	2.9

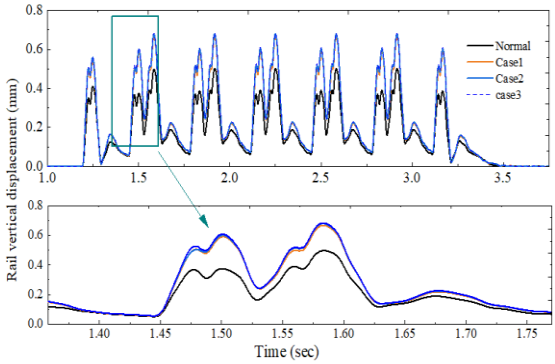
In the simulation, the impact of lateral wind force on both the bridge and vehicle dynamics was quantified as an external force (Raghunathan et al., 2002).

3. Results and Discussion

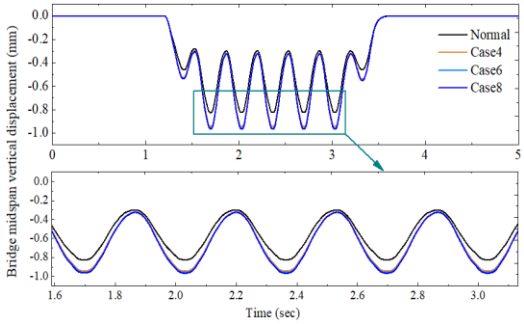
This study highlights the critical influence of track irregularities, passenger's weight, vehicle speed and wind load on the dynamic behavior of prestressed concrete railway bridges. Based on the vehicle-bridge interaction model discussed in section 2.1, and input parameters listed in section 2.3, the bridge-couple system was simulated for various cases and the dynamic responses are presented hereunder.

3.1. Vertical Displacements

The vertical rail and mid-span displacement of railway bridges are critical performance indicators. These vertical displacements under different cases are shown in **Fig. 10**. As shown in the figure, the forces result in fluctuations in the vertical displacement of the rail and bridge, particularly at the mid-span where structural flexure is maximized. Higher amplitudes of track irregularities resulted in increased dynamic responses of the bridge (see Figure 10b). As it can be seen in Figure 10a, even if the maximum track displacement due to wheel load (0.7 mm) is below the limit of 6.35 mm (AREMA, 2010), the vertical displacements of cases 1, 2 and 3 are increased by 72%, 71% and 25%, respectively as compared to the normal condition where it was analysed without any defects (considering design parameters).



(a)



(b)

Figure 10 Vertical Displacements a) Track Rail and b) Bridge's Mid-Span

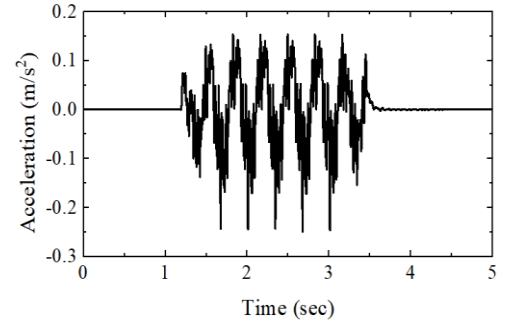
Similarly, the vertical mid-span deflection of the bridge increases accordingly (Figure 10b) without exceeding the deflection limit of L/640 (AREMA, 2010).

3.2. Acceleration Histories

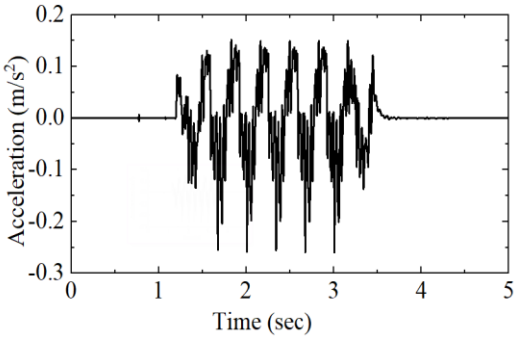
Railway bridges are subjected to dynamic loading conditions due to the moving loads of trains. These dynamic effects can lead to vibrations and accelerations that affect the structural integrity and serviceability of the bridge (Martínez & Elena, 2022). Vertical and

lateral acceleration histories at the bridge's mid-span are presented in Figures 10 and 11, respectively. As shown in Figure 10, the maximum average vertical acceleration curves increase with increasing uncertainty parameters to reach the first peak at normal conditions is 0.23 m/s^2. The highest peak values at cases 1, 5, and 7 are found to be 0.25 m/s^2, 0.272 m/s^2, and 0.29 m/s^2, respectively with an average increment of 17.68 % compared to the normal condition.

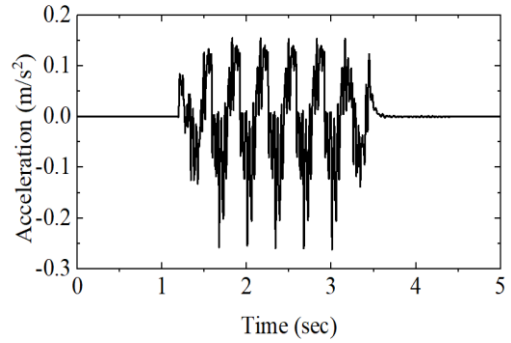
Similarly, from Figure 11, it was observed that the lateral acceleration at normal condition is about 0.04 m/s^2, at case 4, case 6, and case 8 are 0.062 m/s^2, 0.058 m/s^2, and 0.07 m/s^2, respectively. Moreover, it was noticed that the average increase in lateral acceleration compared to the normal condition is 58.3%, and this phenomenon may occur when the forced vibration frequency of a vehicle approaches the natural vibration frequency of a bridge at a specific speed.



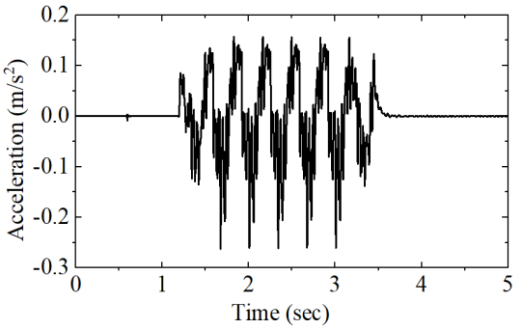
(a)



(b)

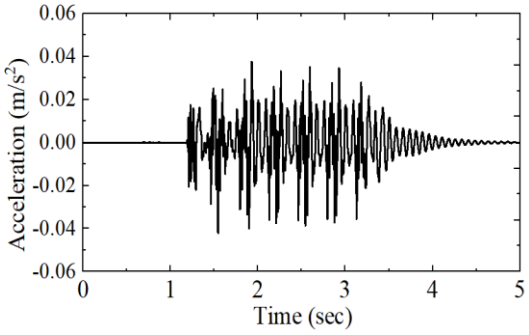


(c)

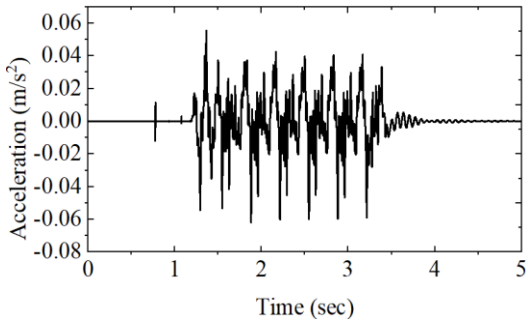


(d)

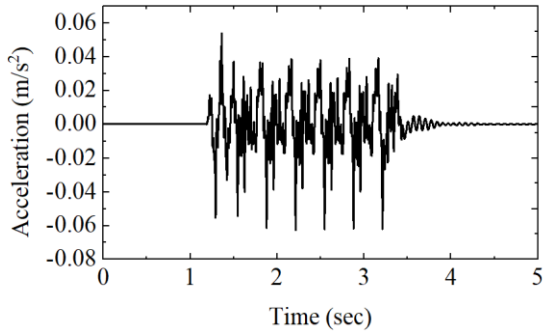
Figure 10 Vertical Acceleration Histories at the Bridge Mid-Span: (a) Normal, (b) Case 1, (c) Case 5, and (d) Case 7



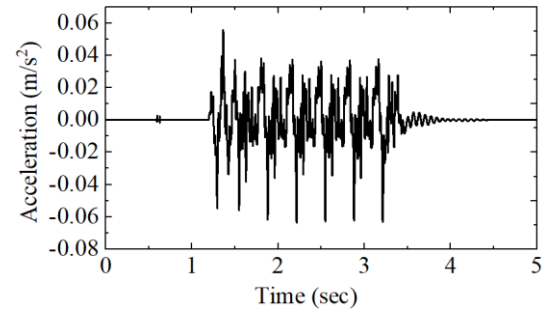
(a)



(b)



(c)



(d)

Figure 11 Lateral Acceleration Histories at the Bridge Mid-Span (a) Normal, (b) Case 4, (c) Case 6, and (d) Case 8.

As vertical loads, such as bridge weight and moving traffic loads are significant on bridges, in the absence of seismic actions, the bridge has experienced higher vertical acceleration than lateral one (Museros et al., 2013).

3.3. Vehicle Speed

The value of vertical bridge acceleration corresponding to the speed value ranging from 60 km/hr to 120 km/hr have been considered and the responses are shown in Figure 12. As shown in the figure, the bridge's mid-span vertical acceleration increases gradually at normal condition (NC) and this behaviour increases linearly for vehicular speeds of 60 km/hr to 90 km/hr. However, for speeds of 90 km/hr and above, the responses of other cases, particularly cases 5 to 8, increases significantly (Figure 12).

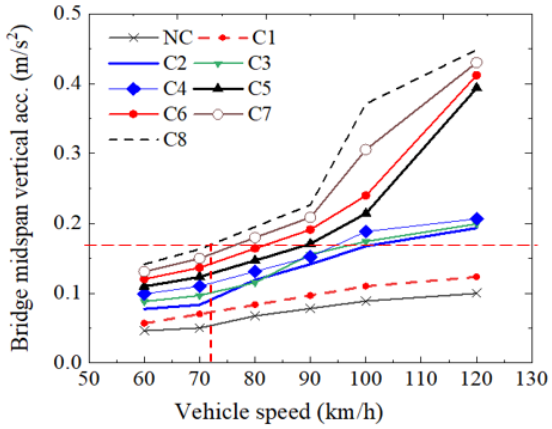


Figure 12 Comparison of Bridge Mid-Span Vertical Acceleration at Different Vehicle Speed

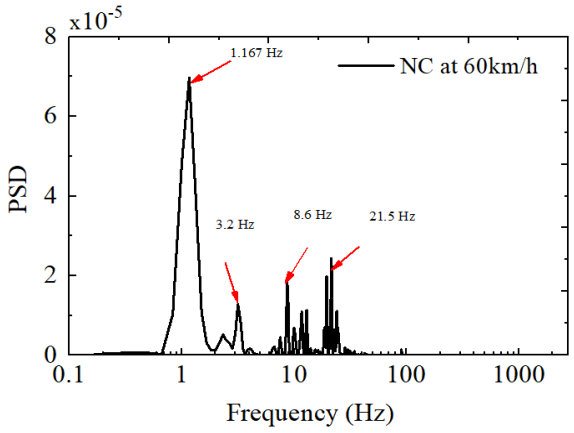
It is also observed that for low speeds (below 70 km/hr), minimal dynamic effects with a maximum vertical acceleration of 0.16 m/s^2 were recorded; the bridge behaviour remained quasi-static and it is within the limit of 0.175 m/s^2 set in standards (AREMA, 2010). This happened due to, at lower speeds, the dynamic effects of train loads are minimized, and displacements are primarily governed by static loads. However, for speeds ranging from 80 to 120 km/hr, the noticeable increase in dynamic response was recorded for case 8 with a peak value of 0.45 m/s^2.

As shown in Figure 12, in some cases, the design standard's maximum vertical acceleration for a passenger train, which is set at 0.175 m/s^2 is exceeded (AREMA, 2010). To limit the train's speed, the acceleration was set to 0.175 m/s^2 and the corresponding speed that meets all cases was chosen, as shown in Figure 12 with a speed limit of 70 km/hr.

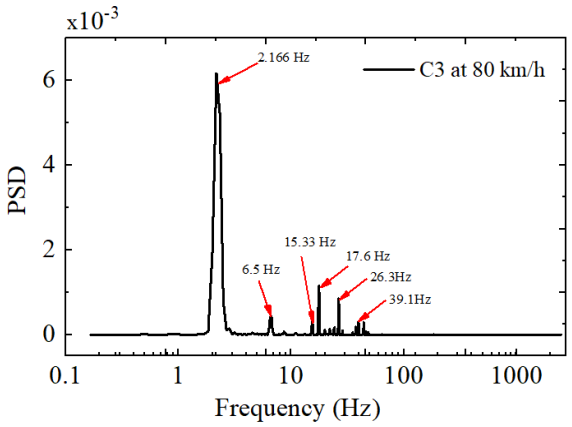
3.4. PSD Analysis

Power Spectral Density (PSD) analysis is an essential method for evaluating the dynamic performance of railway bridges under various excitation including train loads, track irregularities, and environmental forces. It is

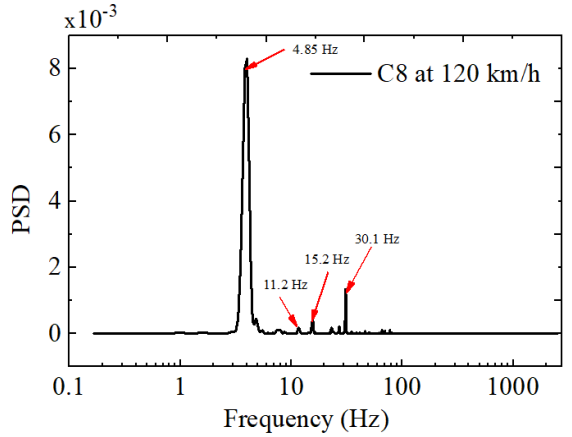
useful in determining how different frequencies of dynamic loads affect the bridge structure (Sorrentino, 2019). Train loads with varying speed, axle load, and axle-configuration generate dynamic responses. In addition, the nature of track irregularities has a direct influence on the frequency of excitation with peak in the PSD values as shown in Figure 13. The peaks in the PSD values of different cases shown in Figure 13 represent dominant frequencies at which the bridge experiences a notable dynamic response. From Figure 13, at peak PSD values, a vibration frequency of 1.17 Hz, 2.16 Hz and 4.85 Hz are observed for normal condition, cases 2 and 8, respectively. The results showed a significant increase in frequencies, and it was found to be critical in case 8 where the 2 Hz to 4Hz limit specified in related research is exceeded (Idris et al., 2016). This can result in severe vibration amplification, leading in excessive dynamic reactions in the bridge and vehicle, a higher possibility of large displacements, reduced passenger comfort due to undesirable vibrations, and cause safety concerns in extreme cases (Rahman et al., 2024; Connolly et al., 2015). These problems need to be mitigated by adjusting operation speeds, regularly inspecting and maintaining track irregularities (Tell, 2021).



(a)



(b)



(c)

Figure 13 PSD of Vertical Mid-Span Bridge Acceleration a) Normal b) Case 3 & c) Case 8

4. Conclusions

From the current study, the following conclusions are drawn.

- There is a good agreement between the field-measured data and the vertical/ lateral responses computed with the new 3D model. The proposed three-dimensional model of the train-bridge dynamic interaction has been validated.
- Under normal circumstances, the vertical accelerations of the bridge and track remain within the specified limits specified in codes and standards, even when the train's speed is increased to 120 km/hr. On the other hand, as can be seen in cases 5 to 8, the bridges' vertical

acceleration is large due to track irregularities compared to other cases. These circumstances led to increased dynamic loads and vibrations on the bridge, necessitating to limit the train's speed to 70 km/hr.

- The track irregularity data collected from field measurement showed that the vertical and lateral deviations were 5 mm and 3 mm, respectively. These values are within the manual-specified limit. However, the uncertainties of track irregularities and other parameters has increased the dynamic loads and affects bridge performances. Hence, collection of tracks' defect data and maintenance intervention should be made regularly.

As track irregularities and train speed significantly affect the dynamic behavior of prestressed concrete railway bridges, effective management and design strategies are crucial for ensuring the safety of these structures under dynamic loading conditions.

Once track irregularities are identified, a systematic maintenance approach should be implemented to correct the issues. This includes, track tamping and alignment, rail grinding, maintenance of rail fastening system and so on.

To enhance the performance of prestressed concrete railway bridges under dynamic loading conditions, key design modifications should focus on increasing stiffness, improving damping, optimizing cross-sectional design, and incorporating high-performance materials and so on.

Examining the effects of seismic actions on railway bridges, investigating innovative materials to improve their dynamic performance, implementing smart sensors and real-time monitoring systems are recommended for future study.

References

Antolín, P., Zhang, N., Goicolea, J. M., Xia, H., Astiz, M. Á., & Oliva, J. (2013). Consideration of nonlinear wheel–rail contact forces for dynamic vehicle–bridge interaction in high-speed railways. Journal of Sound and Vibration, 332(5), 1231-1251.

ARCE (2021). Final Report, Addis Ababa/Sebeta- Mieso- Dewanle Railway Line Post Project Review/Evaluation, African Railway Ceter of Excellence.

AREMA. (2010). Manual for Railway Engineering, American Railway Engineering Association, Washington, DC.

Au, F., Wang, J., & Cheung, Y. (2002). Impact study of cable-stayed railway bridges with random rail irregularities. Engineering Structures, 24(5), 529-541.

Bigoni, D., Engisg-Karup, A.P. and True, H. (2014). Global Sensitivity Analysis of Railway Vehicle Dynamics on Curved Tracks. In Engineering Systems Design and Analysis (Vol. 45844, p. V002T07A023). American Society of Mechanical Engineers.

BRI (2023). BRI Success Stories: The Legacy of the Ethiopia-Djibouti Railway Link. https://research.hktdc.com/en/article/MTU5Njk1NjA1NA (accessed on June 01, 2024).

Bursztyn, D. and Steinberg, D.M. (2002). Rotation designs: orthogonal first-order designs with higher order projectivity. Applied Stochastic Models in Business and Industry, 18(3), pp.197-206.

Chen, G., & Zhai, W. (2004). A new wheel/rail spatially dynamic coupling model and its verification. Vehicle System Dynamics, 41(4), 301-322.

Chen, Y. (2021). Laying the tracks: the political economy of railway development in Ethiopia's railway sector and implications for technology transfer (No. 2021/43). Working Paper.

Claus, H., & Schiehlen, W. (1998). Modeling and simulation of railway bogie structural vibrations. Vehicle system dynamics, 29(S1), 538-552.

Connolly, D.P., Kouroussis, G., Laghrouche, O., Ho, C.L. and Forde, M.C. (2015). Benchmarking railway vibrations–Track, vehicle, ground and building effects. Construction and Building Materials, 92, pp.64-81.

Du Kim, K., & Warnitchai, P. (2009). Dynamic analysis of three-dimensional bridge–high-speed train interactions using a wheel–rail contact model. Engineering Structures, 31(12), 3090-3106.

El-Ghandour, A.I. and Foster, C.D. (2019). Coupled finite element and multibody systems dynamics modelling for the investigation of the bridge approach problem. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 233(10), pp.1097-1111.

Fafard, M., Bennur, M. and Savard, M. (1997). A general multi-axle vehicle model to study the bridge-vehicle interaction. *Engineering Computations*, *14*(5), pp.491-508.

Feng, D. and Feng, M.Q. (2015). Model updating of railway bridge using in situ dynamic displacement measurement under trainloads. Journal of Bridge Engineering, 20(12), p.04015019.

Frýba, L. (1996). Dynamics of railway bridges. Thomas Telford Publishing.

Gao, Q., Cui, K., Li, Z., & Li, Y. (2020). Numerical investigation of the dynamic performance and riding comfort of a straddle-type monorail subjected to moving trains. Applied Sciences, 10(15), 5258.

Garg, V. (2012). Dynamics of railway vehicle systems. Elsevier.

Idris, N. S., Boon, K. H., Kamarudin, A. F., & Sooria, S. Z. (2016). Ambient vibration test on reinforced concrete bridges. In MATEC Web of Conferences (Vol. 47, p. 02012). EDP Sciences.

Karis, T. (2018). Correlation between Track Irregularities and Vehicle Dynamic Response Based on Measurements and Simulations. Master Thesis, Stockholm, Sweden.

Lee, C. H., Kawatani, M., Kim, C. W., Nishimura, N., & Kobayashi, Y. (2006). Dynamic response of a monorail steel bridge under a moving train. Journal of Sound and Vibration, 294(3), 562-579.

Lee, G., Kim, W., Oh, H., Youn, B.D. and Kim, N.H. (2019). Review of statistical model calibration and validation—from the perspective of uncertainty structures. Structural and Multidisciplinary Optimization, 60, pp.1619-1644.

Lei, X., & Noda, N.-A. (2002). Analyses of dynamic response of vehicle and track coupling system with random irregularity of track vertical profile. Journal of Sound and Vibration, 258(1), 147-165.

Lei, X., & Zhang, B. (2011). Analyses of dynamic behavior of track transition with finite elements. Journal of Vibration and Control, 17(11), 1733-1747.

Li, H., Xia, H., Soliman, M., & Frangopol, D. M. (2015). Bridge stress calculation based on the dynamic response of coupled train–bridge system. Engineering Structures, 99, 334-345.

Li, Y., Dong, S., Bao, Y., Chen, K., & Qiang, S. (2015). Impact coefficient analysis of long-span railway cable-stayed bridge based on coupled vehicle-bridge vibration. *Shock and Vibration*.

Liu, K., Reynders, E., De Roeck, G., & Lombaert, G. (2009). Experimental and numerical analysis of a composite bridge for high-speed trains. Journal of Sound and Vibration, 320(1-2), 201-220.

Lou, P., Yu, Z.-W., & Au, F. (2012). Rail–bridge coupling element of unequal lengths for analysing train–track–bridge interaction systems. Applied Mathematical Modelling, 36(4), 1395-1414.

Majka, M., & Hartnett, M. (2009). Dynamic response of bridges to moving trains: A study on effects of random track irregularities and bridge skewness. Computers & Structures, 87(19-20), 1233-1252.

Malveiro, J., Sousa, C., Ribeiro, D. and Calçada, R. (2018). Impact of track irregularities and damping on the fatigue damage of a railway bridge deck slab. Structure and Infrastructure Engineering, 14(9), pp.1257-1268.

Mao, J., Yu, Z., Xiao, Y., Jin, C., & Bai, Y. (2016). Random dynamic analysis of a train-bridge coupled system involving random system parameters based on probability density evolution method. Probabilistic Engineering Mechanics, 46, 48-61.

Martínez G., Elena P. (2022). Effects of moving loads on railway bridges considering the structure of railway track." PhD dissertation, Caminos.

Mengistu, F., & Gebregziabher, H. F. (2021). Assessment of ballast flying in the national railway network of Ethiopia. *Engineering*, *13*(7), 420-429.

Momhur, A., Zhao, Y., Quan, L., Yazhou, S., & Zou, X. (2021). Flexible-Rigid Wheelset Introduced Dynamic Effects due to Wheel Tread Flat. Shock and Vibration, 2021.

Museros, P., Moliner, E. and Martínez-Rodrigo, M.D. (2013). Free vibrations of simply-supported beam bridges under moving loads: Maximum resonance, cancellation and resonant vertical acceleration. Journal of Sound and Vibration, 332(2), pp.326-345.

Nguyen, D.-V., Kim, K.-D., & Warnitchai, P. (2009). Simulation procedure for vehicle–substructure dynamic interactions and wheel movements using linearized wheel–rail interfaces. Finite Elements in Analysis and Design, 45(5), 341-356.

Olmos, J. M., & Astiz, M. A. (2013). Analysis of the lateral dynamic response of high pier viaducts under high-speed train travel. Engineering Structures, 56, 1384-1401.

Raghunathan, R.S., Kim, H.D. and Setoguchi, T. (2002). Aerodynamics of high-speed railway train. Progress in Aerospace sciences, 38(6-7), pp.469-514.

Rahman, A.K., Imam, B. and Hajializadeh, D. (2024). Dynamic Amplification of Railway Bridges under Varying Wagon Pass Frequencies. Infrastructures, 9(3), p.62.

Rücker, W., Hille, F., & Rohrmann, R,. (2006). Guideline for the Assessment of Existing Structures, Final Report-F08a. Federal Institute of Materials Research and Testing.

Shabana, A. (2020). Dynamics of multibody systems. Cambridge university press.

Sorrentino, S. (2019). Power Spectral Density Response of Bridge-Like Structures Loaded by Stochastic Moving Forces. *Shock and Vibration*, *2019*(1).

Su, D., Fujino, Y., Nagayama, T., Hernandez Jr, J. Y., & Seki, M. (2010). Vibration of reinforced concrete viaducts under high-speed train passage: measurement and prediction including train–viaduct interaction. Structure and Infrastructure Engineering, 6(5), 621-633.

Tell, S. (2021). Vibration mitigation of high-speed railway bridges: Application of damping devices in theory and practice (Doctoral dissertation, Kungliga Tekniska högskolan).

Weather & Climate (accessed on May 31, 2024).https://weatherandclimate.com/compare-addis-ababa-and-djibouti

Xia, H., & Zhang, N. (2005). Dynamic interaction of vehicles and structures. Пекін: Science compress–2005.

Xia, H., Zhang, N., & De Roeck, G. (2003). Dynamic analysis of high speed railway bridge under articulated trains. Computers & Structures, 81(26-27), 2467-2478.

Xiao, Y., Luo, X., Liu, J., & Wang, K. (2020). Dynamic response of railway bridges under heavy-haul freight trains. Advances in Civil Engineering, 2020, 1-13.

Yang, Y., Huang, P., Peng, Q., Li, J. and Wen, C. (2019). Statistical delay distribution analysis on high-speed railway trains. Journal of Modern Transportation, 27, pp.188-197.

Youcef, K., Sabiha, T., El Mostafa, D., Ali, D., & Bachir, M. (2013). Dynamic analysis of train-bridge system and riding comfort of trains with rail irregularities. Journal of Mechanical Science and Technology, 27, 951-962.

Yu, Z.-w., & Mao, J.-f. (2018). A stochastic dynamic model of train-track-bridge coupled system based on probability density evolution method. Applied Mathematical Modelling, 59, 205-232.

Yu, Z.-w., Mao, J.-f., Guo, F.-q., & Guo, W. (2016). Non-stationary random vibration

analysis of a 3D train–bridge system using the probability density evolution method. Journal of Sound and Vibration, 366, 173-189.

Zeng, Z.-P., Liu, F.-S., Lou, P., Zhao, Y.-G., & Peng, L.-M. (2016). Formulation of three-dimensional equations of motion for train–slab track–bridge interaction system and its application to random vibration analysis. Applied Mathematical Modelling, 40(11-12), 5891-5929.

Zeng, Z.-P., Zhao, Y.-G., Xu, W.-T., Yu, Z.-W., Chen, L.-K., & Lou, P. (2015). Random vibration analysis of train–bridge under track irregularities and traveling seismic waves using train–slab track–bridge interaction model. Journal of Sound and Vibration, 342, 22-43.

Zhai, W., Wang, K., & Cai, C. (2009). Fundamentals of vehicle–track coupled dynamics. Vehicle system dynamics, 47(11), 1349-1376.

Zhang, N., Xia, H., & Guo, W. (2008). Vehicle–bridge interaction analysis under high-speed trains. Journal of Sound and Vibration, 309(3-5), 407-425.

Zhang, N., Xia, H., Guo, W., & De Roeck, G. (2010). A vehicle–bridge linear interaction model and its validation. International Journal of Structural Stability and Dynamics, 10(02), 335-361.