International Journal of Railway Research, Vol. 10, No. 1, (2023), 69-77

Iran University of Science and Technology

International Journal of

Railway Research

ISSN: 2423-3838

Numerical study of sleeper length effect on dynamic behavior of railway ladder track

J.A. Zakeri[1], H. Heydari[2*], N. Aghabarati[3]

[1]Professor, School of Railway Engineering, Iran University of Science and Technology.

[2]Assistant Professor, School of Railway Engineering, Iran University of Science and Technology.

[3]MSc. Student, School of Railway Engineering, Iran University of Science and Technology.

ARTICLE INFO

Article history:

Received: 07.19.2023

Accepted: 09.09.2023

Published: 09.12.2023

Keywords:

Ladder Railway Track

Ladder Sleeper

Optimal Length

Numerical Modeling

Dynamic Analysis

A B S T R A C T

In recent years, ladder tracks, which are also described as tracks with ladder sleepers, have been developed as a new generation of railway tracks. The structure of the ladder tracks especially includes a combined sleeper consisting of longitudinal and lateral beam elements, which are considered the main support of the rails. Some of the main advantages of using this type of railway track are increasing the stability of the track against longitudinal and lateral forces, reducing dynamic and vibration effects, reducing the risk of buckling, increasing safe train movement, reducing maintenance costs, etc. In this study, the influence of ladder sleeper length on the dynamic behavior of railway tracks was investigated through numerical modeling. For this purpose, a four-layer model including rails and ladder sleepers was simulated based on the finite element method. According to the results obtained from the sensitivity analyses, the maximum acceleration of the sleeper with 6-9 m units is reduced by about 22-40%, compared to the common railway track with B70 concrete sleepers. Also, the maximum displacements of the ladder sleeper with 6-9 m length show a reduction of about 27% compared to the track with the B70 sleeper. Therefore, it can be concluded that the ladder unit with a 6-9 m length shows more dynamic performance generally.

1. Introduction

Ladder tracks are a type of track with longitudinal sleepers that include two longitudinal concrete beams that are connected by transversal steel elements. This system has been developed in recent years as a new generation of railway tracks. The first research on ladder tracks began in Japan, Russia, and France [3, 5, 9]. This type of railway track was first implemented during the construction of the Baulk railway line, and then in 1830, it was applied to the Leeds and Selby lines. The main difference between ballasted and ladder slab track and common ballasted and slab track is in the rail support system. In ladder railway tracks, the rail support is continuously provided with longitudinal sleepers (ladder sleepers), while in ballasted and non-ballasted tracks, the rail seat is supported by discrete lateral sleepers [17].

The studies that have been carried out in relation to ladder railway tracks are divided into three general categories: ballasted ladder tracks, ladder slab tracks, and floating ladder tracks. From the studies related to the ballasted ladder tracks, it can be found that the ballasted ladder track is effective in reducing vibration at high speed and frequency, so the shape of the sleeper can induce changes in the field of ballast vibration. The deformation, velocity and

*Corresponding author

Email address: h_heydari@iust.ac.ir

[DOI: 10.22068/ijrare.325]

acceleration responses of ladder track components are much lower than those of conventional ballasted tracks. Also, the vibration acceleration and deformation responses of the components of the ballasted ladder track are less than those of the common ballasted track [9]. Ballasted tracks and ladder tracks with elastic elements can provide different effects of vibration reduction in different cases [14-16]. Also, the length of the ladder units has an effect on the dynamic behavior of the track, which, of course, should be further investigated [3]. According to the experimental tests carried out on panels with different crib heights, this component has a significant contribution to the lateral resistance of the ladder track. In fact, due to the passive resistance of the ballast between the two longitudinal beams, the higher amount of crib ballast increases the ballast/sleeper interaction and thus reduces the lateral movement of the ladder sleeper. Finally, ladder sleepers increase the lateral resistance of the ballasted track and also reduce the use of ballast materials [4]. Ladder slabs also have good vibration reduction characteristics compared to normal slabs, which is mainly reflected in the vertical acceleration of a bridge [6]. The performance of the floating ladder track in reducing the measured vibration is better than that of the normal ballast track [1, 7]. It has been quantitatively confirmed in the studies that the floating ladder track showsbetter environmental behavior in vibration compared to the non-ballasted track. From the experiment conducted on the effect of reducing the vibration of a floating ladder track, it can be concluded that the first natural frequency of the floating ladder track is around 33 Hz [10]. According to a parametric study, the multi-point approximation method is very suitable for optimizing the mechanical properties of the ladder track to reduce vibrations [12-13].

Considering the various advantages and disadvantages that can be expected if ladder tracks are used, and since the effects and dynamic and vibration characteristics of the length of this type of track have been limited in the technical literature, in this research, an attempt was made to numerically study the effect of different ladder sleeper lengths on the dynamic behavior of the ladder track. Therefore, in the present study, a multi-layer finite element model including rail, sleeper, upper ballast, lower ballast, rail pad, and ladder sleepers was made. In this regard, the Euler-Bernoulli beam element was used to model the rail and ladder sleeper, the spring-damper element to simulate the pad under the rail, and the set of mass-spring-damper elements to build the ballast (upper and lower) and subgrade layers. The results of the analysis and investigations are described below.

2. Ladder track modeling

In this study, a numerical model of the ballasted track with ladder sleepers was built based on the finite element method. This finite element model is a multi-layered mass-spring-damper model, including rail, sleeper, upper ballast, lower ballast, rail pad, and ladder sleepers. The modeling of a 72-meter-long ladder railway track, including the assembled components with mass-spring-damper elements, was done. The assumptions considered in creating the model examined in this study for the dynamic analysis of the track are:

- The track is modeled in 2D to minimize the computational costs of the 3D model.
- Only the effect of vertical dynamic loads is considered in the modeling.
- The track's parameters are assumed to be linear and geometrically fixed.
- Rail layers and ladder sleepers are modeled as Euler-Bernoulli beam elements.
- The top and bottom ballast layers are simulated with a set of mass-spring-damper elements.
- The load is modeled as a moving mass (wheel motion modeling), and the axial load of the vehicle is applied to the center of the rotating wheel.

In the current research, the modeling of the ballast ladder track was simulated based on the finite element method according to Figure (1) as 4 layers with ladder units. In this regard, the ladder track has been modeled as a multilayer, including the following components and parts:

- The first layer includes rails and pads under the rails, where the rails are modeled as Euler-Bernoulli beams, and the pads are modeled with spring-damper elements.
- The second layer contains ladder sleepers simulated by Euler-Bernoulli beam elements.
- The third and fourth layers include spring-damper-mass elements of the upper and

[DOI: 10.22068/ijrare.325]

lower ballast layers; each of the upper and lower ballast layers is modeled separately.

In this study, only the effect of vertical dynamic loads has been considered in the modeling, and

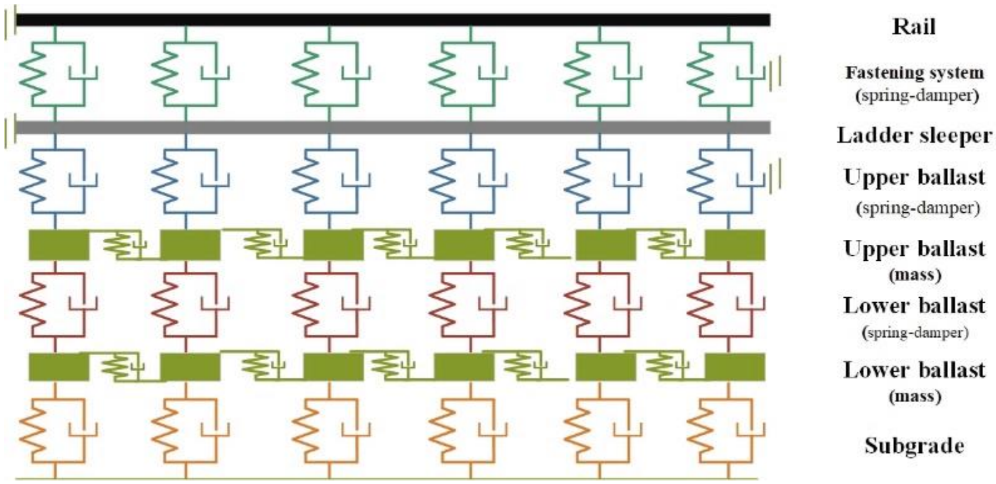

Figure 1. Schematic of the longitudinal model of the four-layer ladder track.

One of the best approaches for rail modeling is to use the Euler-Bernoulli beam element. Ladder sleepers can also be modeled using the Euler-Bernoulli beam element. The specifications of the components and materials of the ladder track are presented in Table 1. As seen in Figure 1, in the 4-layer model, the upper and lower ballast layers are modeled as mass-spring-damper. The specifications of the spring, damper, and ballast mass are listed in Table 2.

3. Specifications of ladder track components

The total length of the ladder track model, with the aim of more accurate simulation and less error, is 72 m. To investigate the effect of the length of ladder units, five different lengths of 4.5, 6, 9, 12, and 18 m were simulated. The specifications of the railway track components are given in Tables 1 and 2. [2, 6, 11]

the effects of lateral and longitudinal loads have not been applied. The vertical load is modeled as a moving mass (wheel motion modeling), and the weight of the vehicle wheel is applied to the center of the rotating wheel at a constant speed. The axial load was considered to be 14250 kg. The specifications of the wheels modeled can be seen in Table 3.

The mesh size of the rail elements and the length of the ladder sleeper elements are considered to be 0.05 m. An explicit dynamic analysis is used in this modeling. The desired outputs are rail displacement and acceleration, ladder sleeper, and upper and lower ballast. For the rail, upper ballast, and lower ballast, the reference point is in the middle of the track, and for the sleeper, it is in the middle of the middle sleeper. The duration of the analysis is 0.02s according to the loading of the article and with a time interval of 0.001s. The duration of the analysis was considered to be 1.44 seconds due

Table 1. Mechanical specifications of rail and ladder sleeper.

Item	Parameter	Value
Rail	Cross-section dimensions	Rectangular: 0.06m×0.18m
	Density	7850 kg/m^3
	Rail type	UIC60
	Modulus of elasticity	$2.1 \times 10^{11} N/m^2$
	Poisson's ratio	0.3
Ladder sleeper	Cross-section dimensions	Rectangular: 0.6m×0.2m
	Density	2500 kg/m^3
	Modulus of elasticity	$3.1 \times 10^{10} N/m^2$
	Poisson's ratio	0.3

[DOI: 10.22068/ijrare.325]

Table 2. Characteristics of ballast and subgrade layers in the ladder track model.

Item	Ballast		Fastening	Subgrade	Shear interlocking stiffness
	Upper ballast	Lower ballast			
Stiffness (kN/mm)	125	110	80	150	78.4
Damping (N.s/m)	58800	58800	75000	31150	80000
Mass (kg)	235	210	-	-	-

Table 3. Wheel specifications and loading in the model.

Parameter	Value
Radius	0.42m
Density	$7850\ kg/m^3$
Modulus of elasticity	$2.1 \times 10^{11} N/m^2$
Poisson's ratio	0.3
Wheel load	71250 N

to the length of the track of 72 m and the passing speed of 25 m/s. The outputs of these simulations have been analyzed both in the form of time history and in the form of frequency analysis, which will be explained below.

4. Investigation of ladder Sleeper length

In this section, the influence of the length of the ladder sleeper as one of the most important geometric characteristics affecting the behavior of the line was investigated by changing the length of the parts in the range of 4.5 to 18 m. The effect of this geometric characteristic on the dynamic and vibrational behavior of the railway track has been analyzed in order to find the optimal length of the ladder sleeper, the results of which are explained below. In Figure 2, the time history changes of the acceleration created at the sleeper location can be seen for the ladder track with different lengths as well as the common track (with concrete B70 sleepers).

In Figure 3, the maximum and average values of sleeper acceleration changes for ladder units with different lengths (4.5 to 18 m) are compared. As can be seen from these graphs, the maximum and average (RMS) values of rail and sleeper acceleration decrease with the increase in the traverse length until it is minimized in the length range of 6 to 12 m, and then in long sleepers (above 12 m), the trend is increasing. As an example, the maximum acceleration of the sleeper in the ladder track with the length of 9 m

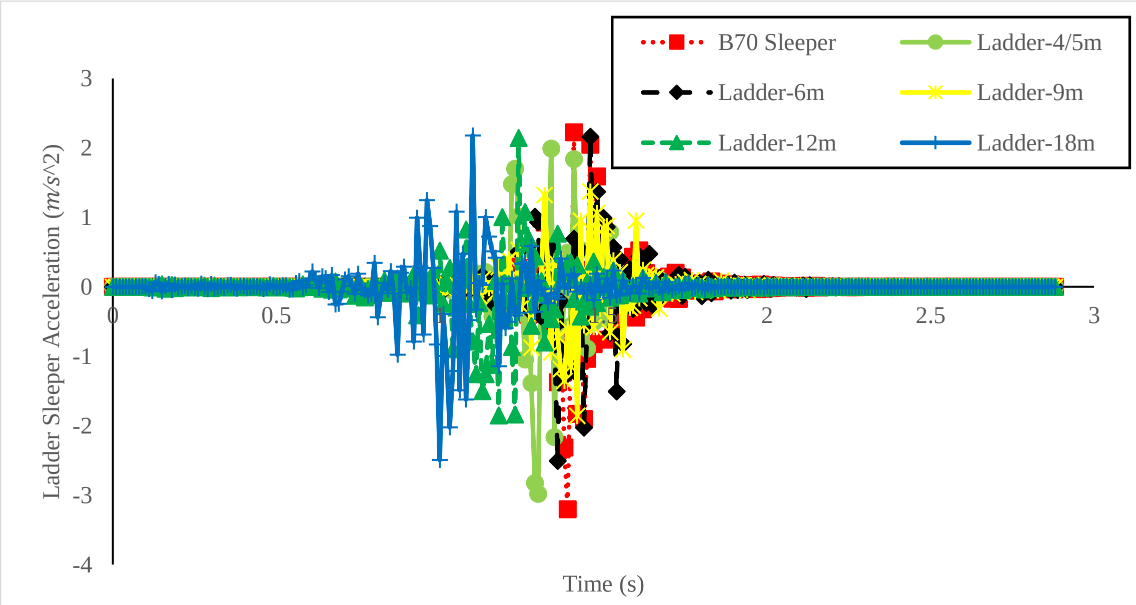

Figure 2. time history of sleeper acceleration with changing the length of the ladder sleeper.

[DOI: 10.22068/ijrare.325]

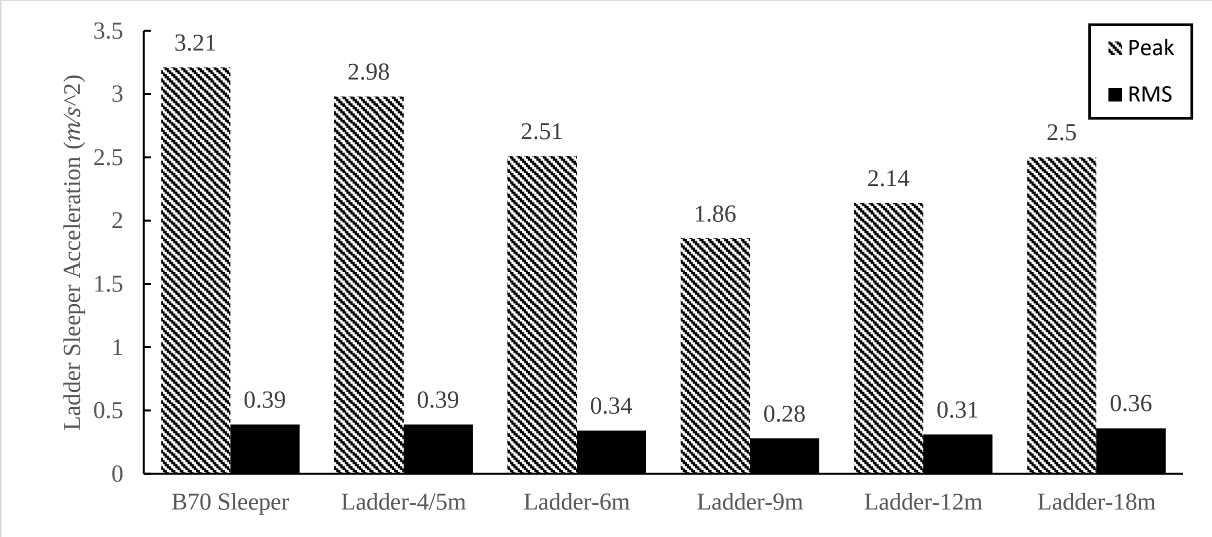

Figure 3. Comparison of the maximum and average acceleration of the sleeper with the length of the ladder sleeper.

(1.9 m/s2) compared to that with the length of 4.5 m (3 m/s2) and the concrete B70 sleeper (3.2 m/s2) has decreased by about 36 and 40 percent, respectively. Therefore, according to these results, it can be seen that the amount of acceleration created in the 9-meter ladder sleeper will be minimized, which means better dynamic performance of the 9-meter sleeper compared to other lengths from the perspective of accelerations created in the railway track.

In Figure 4, the changes in the time history of the displacement created at the rail location for ladder tracks with different ladder units and also common railway tracks (with concrete B70 sleepers) can be seen.

In Figure 5, the values of maximum rail displacement with ladder sleepers of different lengths (4.5 to 18 m) are compared. As can be seen from these graphs, the value of the maximum displacement of the rail decreases with the increase of the sleeper length until it is minimized in the length range of 6 to 12 m, and then in long sleepers (above 12 m), it shows increasing changes. Therefore, according to these results, it can be seen that the amount of displacement created in the ladder sleeper with a length of 6 and 9 m will be minimized. This means the better dynamic performance of 6 and 9 m sleepers compared to other lengths from the

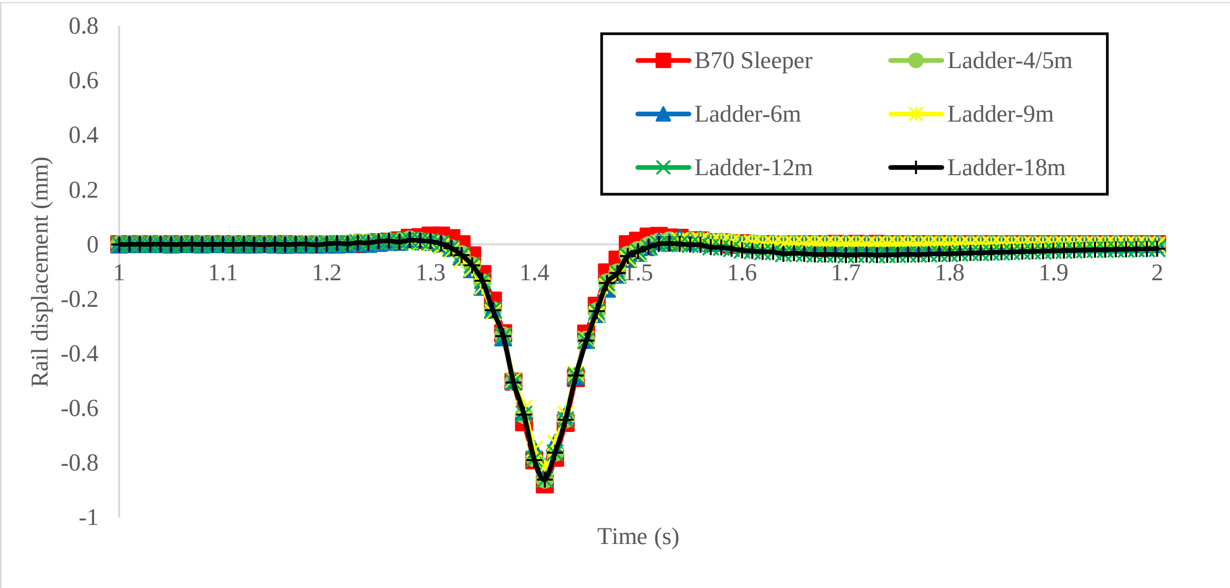

Figure 4. Time history of rail displacement with ladder sleeper length.

[DOI: 10.22068/ijrare.325]

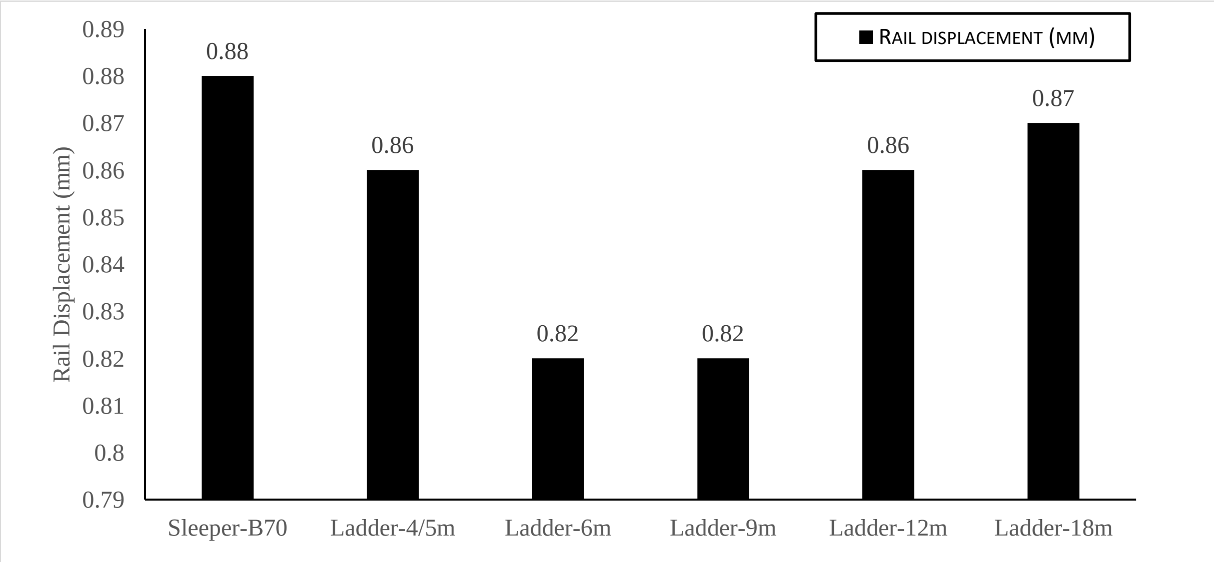

Figure 5. Comparison of the maximum displacement of the rail with the change of the ladder sleeper length.

point of view of the displacement created in the railway track.

In Figure 6, the Vibration Acceleration Level (VAL) created at the location of the sleeper for the ladder track with different lengths and also the common track (with concrete B70 sleepers) can be seen. The VAL value of the sleeper can be calculated as follows:

$$VAL(f_i) = 20\log_{10}\frac{a_{rms}(f_i)}{a_0} \quad (1)$$

Where $a_{rms}(f_i)$ is the root mean square acceleration value in 1/3 octave band frequency and (f_i), $a_0 = 25 \times 10^{-6}\ m/s^2$ is the reference acceleration.

In Figure 7, the vibration acceleration levels for the ladder track with different lengths (4.5 to 18 meters) are compared. As can be seen from these graphs, the vibration acceleration level of the traverse increases up to the length of the sleeper of 9 m and then reaches its minimum value of 65.6 dB during the 9 m length of the sleeper, and after that, the trend is increasing. For example, the minimum vibration acceleration level of the sleeper in the ladder track with a length of 9 m (65.6 dB) compared to the 4.5 m

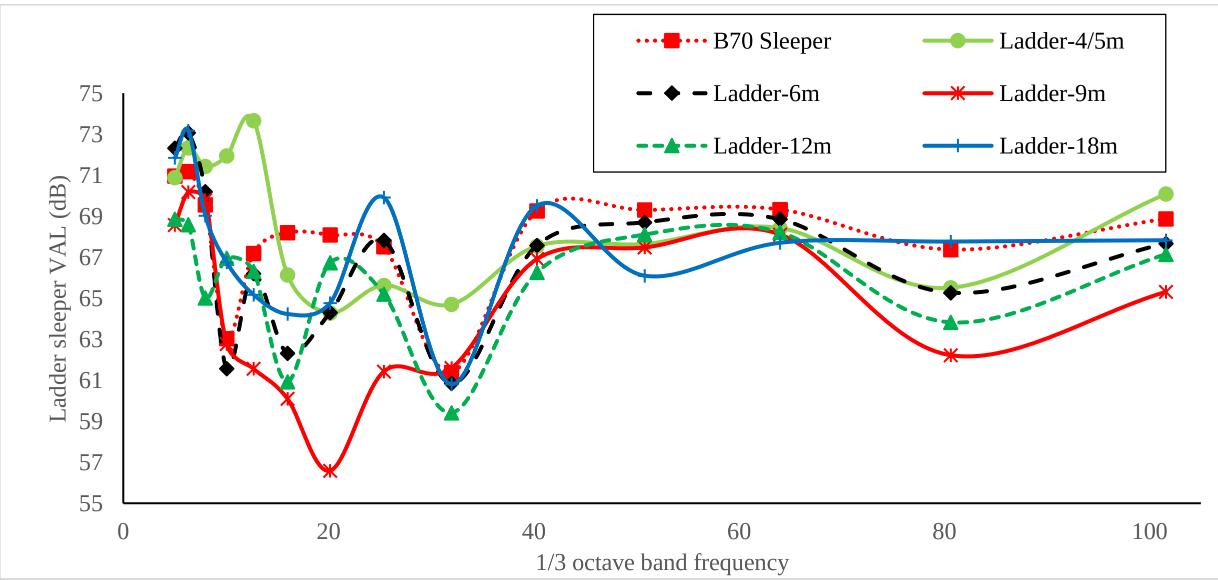

Figure 6. Vibration Acceleration Level (VAL) of sleeper with ladder sleeper length.

[DOI: 10.22068/ijrare.325]

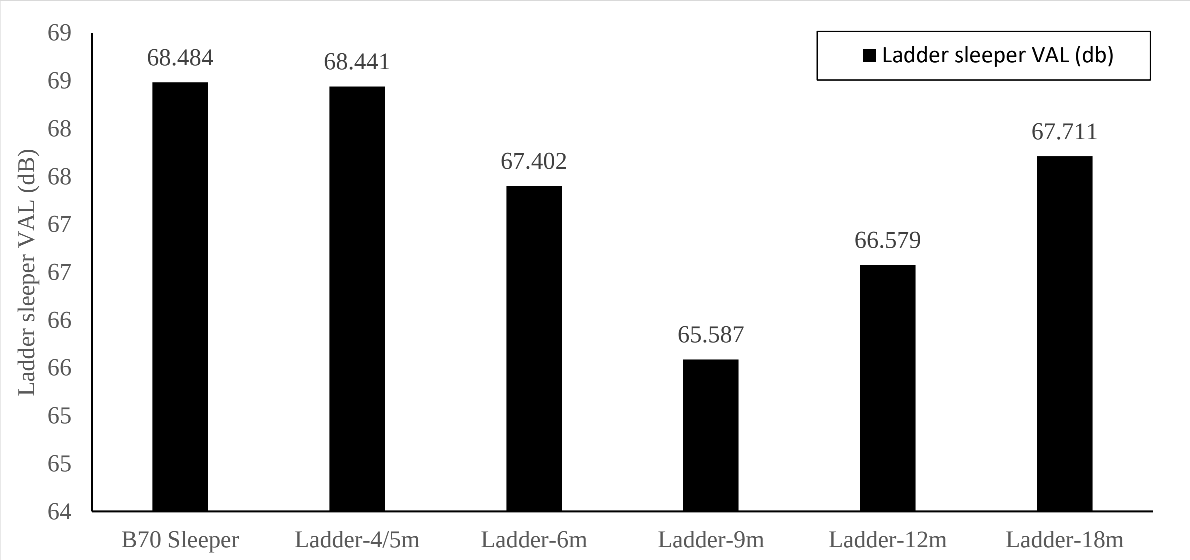

Figure 7. Comparison of sleeper Vibration Acceleration Level (VAL) in ladder sleepers with different lengths.

and the concrete B70 sleeper (68.4 dB) has decreased by about 4%. This means that the lowest vibration acceleration level occurs in the rail and sleeper during the 9-meter sleeper units. Therefore, according to these results, it can be seen that the vibration acceleration level created in the ladder sleeper with a length of 9 m will be minimized. This means better dynamic performance of 9-meter sleepers compared to other lengths from the point of view of the vibration acceleration level created in the railway track.

In Figure 8, the Transfer Loss (TL) created for ladder tracks with different lengths and the common track (with concrete B70 sleepers) can be seen. The TL value between rail and ballast is calculated as follows:

$$TL(f_i) = 20\log_{10}\frac{a_{rail}(f_i)}{a_{ballast}(f_i)} \quad (2)$$

Where $a_{rail}(f_i)$ and $a_{ballast}(f_i)$ are the acceleration responses at the rail and ballast locations, respectively.

In Figure 9, the transfer loss (TL) of rail for the ladder track with different lengths (4.5 to 18 meters) is compared. As can be seen from these graphs, the amount of transfer loss of rail along

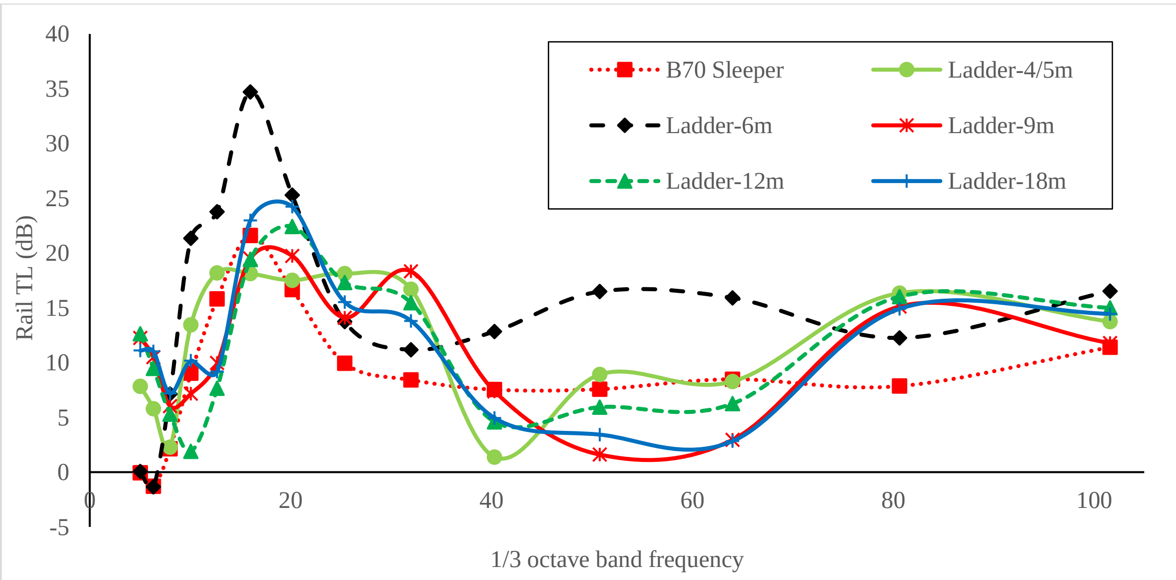

Figure 8. Transfer Loss (TL) by changing the length of ladder sleeper.

[DOI: 10.22068/ijrare.325]

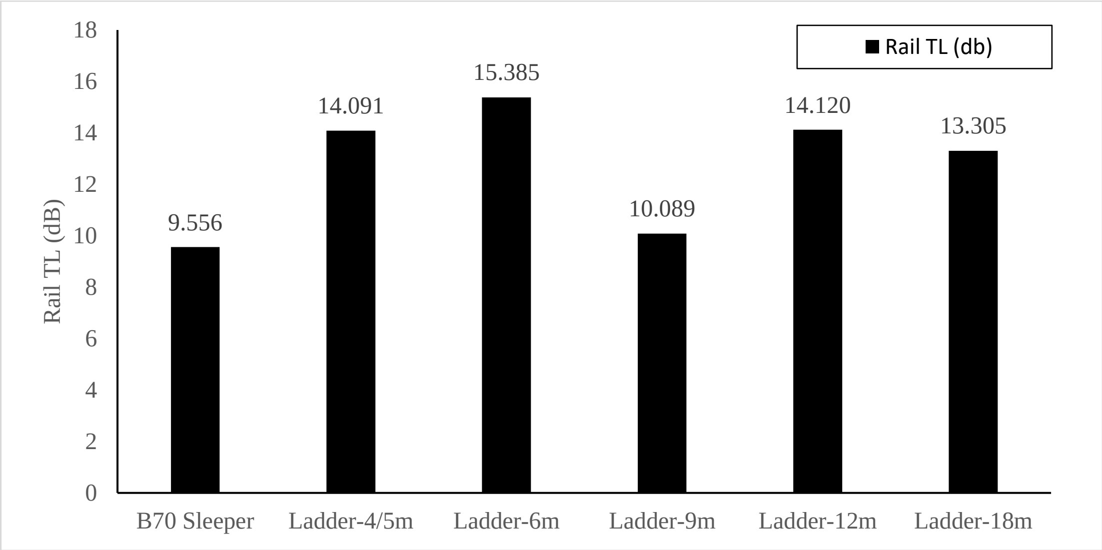

Figure 9. Comparison of Transfer Loss (TL) for ladder sleepers with different lengths.

the length of the 6 m sleeper units is 15.4 dB, which shows the highest amount of transfer loss compared to other lengths. Therefore, according to these results, it can be seen that the highest transfer loss will be in the ladder sleeper with a length of 6 m. This means better dynamic performance of 6 m sleepers compared to other lengths from the point of view of the transfer loss created in the railway track.

5. Conclusion

In this study, the dynamic and vibrational responses of railway ladder tracks with different lengths were investigated using a series of sensitivity analyses. By analyzing the results, it can be identified that the optimal ladder sleeper length is 6-9 m units which shows better performance from dynamic and vibration points of view. In general, the most important results that can be enumerated from the time and frequency analyses are listed as follows:

a. In the time history domain analyses, the maximum acceleration of the sleeper with a length of 6 m (2.5 m/s2) and 9 m (1.9 m/s2) compared to the common track with concrete B70 sleepers (2.3 m/s2) decreases by about 22% and 40%, respectively. Also, the maximum rail displacements in the ladder track with the length of 6 and 9 m (0.82 mm) compared to the common track with concrete B70 sleepers (0.88 mm) show a reduction of about 7%.
b. In the frequency domain analyses, the vibration acceleration level (VAL) of the sleeper with a length of 6 m (67.4 dB) and 9 m (65.6 dB), shows a reduction of about 2 and 3 dB, respectively, compared to the vibration acceleration level of the concrete B70 sleeper (68.5 dB). In addition, the amount of transfer loss (TL) of the rail in the ladder sleeper with a length of 6 and 9 m is 15.4 dB and 10 dB, respectively, which, compared to the common track (9.5 dB), indicates a noticeable reduction in vibrations when the ladder sleeper is used.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

[DOI: 10.22068/ijrare.325]

References

[1] Jemema, M. W. (2015). Dynamic comparison of Conventional ballasted track Versus Ballasted ladder track [ADDIS ABABA UNIVERSITY]. http://etd.aau.edu.et/handle/123456789/18553

[2] Heydari, H., Zakeri, J., Esmaeili, M., & Varandas, J. (2017). Field study using additional rails and an approach slab as a transition zone from slab track to the ballasted track. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 232, 095440971770852. https://doi.org/10.1177/0954409717708527.

[3] Asanuma, K. (2004). Ladder track structure and performance. Railway Technol Avalanche, 6, 35.

[4] Younesian, D., Mohammadzadeh, S., & Esmailzadeh, E. (2006). Dynamic performance, system identification and sensitivity analysis of the ladder track. 7th World Congress on Railway Research.

[5] Ma, M., Liu, W., Li, Y., & Liu, W. (2017). An experimental study of vibration reduction of a ballasted ladder track. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 231(9), 1035–1047.

[6] Qu, X., Ma, M., Li, M., Cao, Y., & Liu, W. (2019). Analysis of the vibration mitigation characteristics of the ballasted ladder track with elastic elements. Sustainability, 11(23), 6780.

[7] Zakeri, J. A., Ebrahimi-Gholami, O., Hassan Liravi, H., & Satar-Boroujen, G. (2020). Numerical investigation on train-induced environmental vibration in floating ladder tracks. Journal of Theoretical and Applied Mechanics, 58(4), 871–883. https://doi.org/10.15632/jtam-pl/126319.

[8] OKUDA, H., ASANUMA, K., MATSUMOTO, N., & WAKUI, H. (2004). Dynamic load, resistance and environmental performance of floating ladder track. Quarterly Report of RTRI, 45(3), 149–155.

[9] Ma, M., Jiang, B., Li, M., & Sun, X. (2017). A Laboratory Test on the Vibration Mitigation Efficiency of Floating Ladder Tracks. Procedia Engineering, 199, 2705–2710. https://doi.org/https://doi.org/10.1016/j.proeng.2017.09.570 .

[10] Xia, H., Deng, Y., Zou, Y., De Roeck, G., & Degrande, G. (2009). Dynamic analysis of rail transit elevated bridge with ladder track. Frontiers of Architecture and Civil Engineering in China, 3(1), 2–8. https://doi.org/10.1007/s11709-009-0001-x.

[11] Heydari, H., Varandas, J., Esmaeili, M., & Zakeri, J. (2017). Investigating the Influence of Auxiliary Rails on Dynamic Behavior of Railway Transition Zone by a 3D Train-Track Interaction Model. Latin American Journal of Solids and Structures, 14. https://doi.org/10.1590/1679-78253906.

[12] Jing, G., Aela, P., & Fu, H. (2019). The contribution of ballast layer components to the lateral resistance of ladder sleeper track. Construction and Building Materials, 202, 796–805.https://doi.org/https://doi.org/10.1016/j.conbuildmat.2019.01.017.

[13] Jin, H., Liu, W., & Zhou, S. (2015). Optimization of Vibration Reduction Ability of Ladder Tracks by FEM Coupled with ACO. Shock and Vibration, 2015. https://doi.org/10.1155/2015/484827.

[14] Hosking, R., & Milinazzo, F. (2007). Floating ladder track response to a steadily moving load. Mathematical Methods in the Applied Sciences, 30, 1823–1841. https://doi.org/10.1002/mma.871.

[15] Heydari, H., Zakeri, J., & Esmaeili, M. (2021). Evaluating the elastic sleeper efficiency in reduction of railway ground vibrations by in situ impact-response test. International Journal of Vehicle Noise and Vibration, 17(3–4), 237–252.https://doi.org/10.1504/IJVNV.2021.123442.

[16] Zakeri, J., Esmaeili, M., & Heydari, H. (2015). A field investigation into the effect of under sleeper pads on the reduction of railway-induced ground-borne vibrations. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 230. https://doi.org/10.1177/0954409714565499.

[17] Yan, Z.-Q., Markine, V. L., Gu, A.-J., & Liang, Q. (2013). Optimization of the dynamic properties of the ladder track system to control rail vibration using the multipoint approximation method. Journal of Vibration and Control, 20, 1967–1984. https://doi.org/10.1177/1077546313480539.

[DOI: 10.22068/ijrare.325]