ANALYSIS OF LOCOMOTIVE DRIVER RIDE COMFORT

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Abstract. Railway transport belongs to the most important kinds of transport. It is ensured by rail vehicles, which are locomotives and wagons. Locomotives are the traction vehicles, which serve for pulling (sometimes for pushing) wagons. Locomotives are driven by a person in a cabin, who is called a locomotive driver. The competencies and responsibilities of a locomotive driver are serious and important for safe and reliable operation of a train. Therefore, it is important, that a driver works in suitable working conditions. From the mechanics point of view, a locomotive is a mechanical system, which consists of rigid and flexible elements. During locomotive running on a track, the locomotive driver is exposed to mechanical vibrations due to vehicle excitations caused by track irregularities presence. The goal of the presented research is to analyse the effects of the locomotive running on the driver ride comfort. A two bogie four axle locomotive is considered. A simplified mathematical model of a locomotive with the suspended seat is derived by means of the Lagrange's equations of the second kind method. Further, a multibody model of a locomotive is created in a commercial multibody software Simpack. The locomotive driver ride comfort is evaluated for the chosen running speeds and the defined track irregularities. Track irregularities are defined by means of the power spectral density function of ERRI B176. The locomotive driver ride comfort is assessed by means of the valid ride comfort indices and standards.

Keywords: locomotive, ride comfort, accelerations, multibody model, excitation.

Introduction

Railway transport is one of the most effective and environmentally friendly kinds of transport [1-5]. It ensures transportation of passengers and tonnes of goods for shorter as well as for long distances [6-9]. Many kinds of rail vehicles are used for railway transport [10-14]. There are mainly passenger wagons and freight wagons, which are towed by locomotives. Further, there are also multiple units intended for regional and long-distance transport of passengers. If it is focused on locomotives, there are recently used locomotives with an independent as well as with a dependent traction system. Locomotives with independent traction system are usually equipped with a diesel combustion engine [15]. Recently, there are new trends to apply batteries or hydrogen fuels as effective and pure sources of power for independent locomotives [16-20]. On the other hand, line-powered locomotives and driven by electric motors are more and more spread in practice [21]. Regardless of the kind of power, these locomotives are always exposed to dynamical effects when running. These dynamical effects are caused by a combination of many factors, such as track irregularities, running speed, railway track geometry, design of a locomotive and others [22; 23]. These dynamical effects can have deteriorating consequences on individual structural units of the locomotive and on the locomotive crew. Rail vehicles are evaluated from two main points of view, namely, from the safety point of view and from the ride comfort for passengers. In case of running safety, there are evaluated forces in the wheel/rail contact, such as vertical and lateral wheel forces, further derailment quotient and the sum of guidance forces [24-26]. Moreover, there are evaluated forces ratios for running through track switches and stability in straight track sections [27; 28]. In terms of evaluation of ride comfort for passengers, selected places in the wagon body are evaluated. Accelerations are identified to assess the ride comfort. Evaluation of ride comfort is performed based on procedures defined in corresponding standards. The European standard EN 12299:2009 [29] is the main document, which prescribes the main requirements for measured places in a wagon, weighing filters should be applied for acceleration signals and mathematical formulations for ride comfort calculations. There is much research focused on investigation of ride comfort for passengers. However, there is lack of works, which evaluate ride comfort of a person, who drives the locomotive. Even the standard described above does not set out procedures and rules, how the ride comfort could be evaluated for a locomotive driver although he spends more time in the vehicle than a passenger in the wagon. It is the main motivation of the presented research.

Materials and methods

The ride comfort is overall feelings that a person perceives during rail vehicle running. These feelings include many factors, such as temperature, lighting, humidity, and also mechanical vibrations.

From the mechanics point of view, mechanical vibrations are the most important for evaluation of ride comfort in a rail vehicle. Mechanical vibrations can cause several levels of discomfort, which depends on the intensity and exposure time. Quantifying of mechanical vibrations is based on identifying of acceleration caused by mechanical vibration of a rail vehicle. Transmission of vibrations from a vehicle body to a human body is quite a complicated mechanism. In principle, two methods are applied for ride comfort evaluation, namely, direct and indirect method [30; 31]. For purposes of the presented research, the indirect method was applied. It means that the ride comfort is assessed by means of results of acceleration measurements, while simulation computations were employed in the research. A four-axle two-bogie locomotive has been chosen for evaluation of the driver ride comfort. The locomotive is equipped with two level suspension systems. The primary suspension system connects wheelsets with bogie frames and the secondary suspension connects bogie frames with the locomotive body. These suspension systems include coil springs and hydraulic dampers, which are situated in both primary and secondary suspension systems. In case of simplified dynamical models, vertical oscillations are the most important. Figure 1 shows one of the possible simplified planar dynamical models of the investigated locomotive. As it can be seen, this model consists of four rigid bodies interconnected by means of viscoelastic couplings. The rigid bodies are bogies frames, the locomotive body and driver seat.

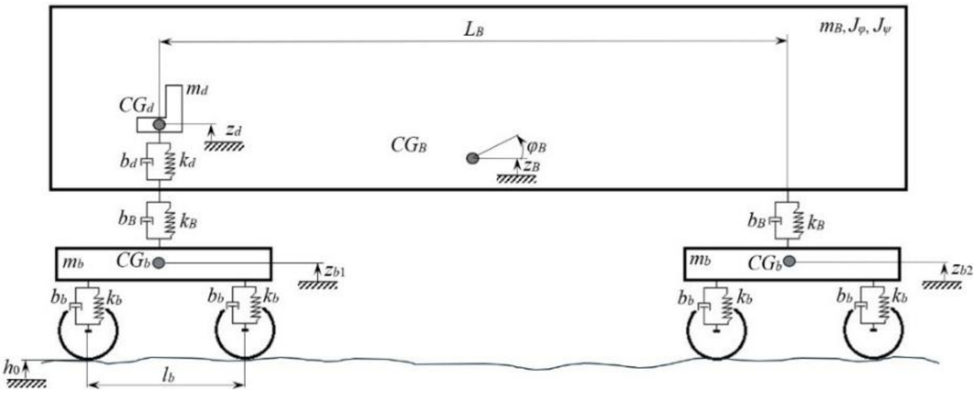

Fig. 1. **Simplified model of the locomotive – vertical oscillation**

The derived five equations of motion describing locomotive vertical oscillations are in a matrix form as follows:

$$\begin{bmatrix} m_b & 0 & 0 & 0 & 0 \\ 0 & m_b & 0 & 0 & 0 \\ 0 & 0 & m_B & 0 & 0 \\ 0 & 0 & 0 & J_B & 0 \\ 0 & 0 & 0 & 0 & m_d \end{bmatrix} \cdot \begin{bmatrix} \ddot{z}_{b1} \\ \ddot{z}_{b2} \\ \ddot{z}_B \\ \ddot{\varphi}_B \\ \ddot{z}_d \end{bmatrix} + \begin{bmatrix} 2 \cdot b_b + b_B + b_d & 0 & -b_B & (b_B - b_d) \cdot \frac{L_B}{2} & -b_d \\ 0 & 2 \cdot b_b + b_B & -b_B & -b_B \cdot \frac{L_B}{2} & 0 \\ -b_B & -b_B & 2 \cdot b_B & 0 & 0 \\ (b_B - b_d) \cdot \frac{L_B}{2} & -b_B \cdot \frac{L_B}{2} & 0 & b_B \cdot \frac{L_B^2}{2} + b_d \cdot \frac{L_B^2}{4} & b_d \cdot \frac{L_B}{2} \\ -b_d & 0 & 0 & b_d \cdot \frac{L_B}{2} & b_d \end{bmatrix} \cdot \begin{bmatrix} \dot{z}_{b1} \\ \dot{z}_{b2} \\ \dot{z}_B \\ \dot{\varphi}_B \\ \dot{z}_d \end{bmatrix} +$$

$$\begin{bmatrix} 2 \cdot k_b + k_B + k_d & 0 & -k_B & (k_B - k_d) \cdot \frac{L_B}{2} & -k_d \\ 0 & 2 \cdot k_b + k_B & -k_B & -k_B \cdot \frac{L_B}{2} & 0 \\ -k_B & -k_B & 2 \cdot k_B & 0 & 0 \\ (k_B - k_d) \cdot \frac{L_B}{2} & -k_B \cdot \frac{L_B}{2} & 0 & k_B \cdot \frac{L_B^2}{2} + k_d \cdot \frac{L_B^2}{4} & k_d \cdot \frac{L_B}{2} \\ -k_d & 0 & 0 & k_d \cdot \frac{L_B}{2} & k_d \end{bmatrix} \cdot \begin{bmatrix} z_{b1} \\ z_{b2} \\ z_B \\ \varphi_B \\ z_d \end{bmatrix} = \begin{bmatrix} k_b \cdot \left(h_0 \cdot e^{i \cdot \omega \cdot t} + h_0 \cdot e^{i \cdot \omega \left(t - \frac{l_b}{v} \right)} \right) \\ k_b \cdot \left(h_0 \cdot e^{i \cdot \omega \left(t - \frac{L_B}{v} \right)} + h_0 \cdot e^{i \cdot \omega \left[t - \left(\frac{L_B + l_b}{v} \right) \right]} \right) \\ 0 \\ 0 \\ 0 \end{bmatrix}. \quad (1)$$

The considered simplified planar model has five generalised coordinates designated as z_{b1}, z_{b2} z_B, φ_B and z_d. The mass and inertia properties of the considered bodies are characterized by the following quantities: m_b are masses of bogies frames, m_B is the locomotive body mass, m_d is the driver seat mass and I_φ is the moment of inertia around the lateral axis. Further, the quantities k_b, k_B are stiffnesses of primary and secondary springs, respectively, and b_b, b_B are damping coefficients of the primary and secondary dampers. Stiffness of the driver seat suspension is k_d and its damping is b_d.

The derived simplified locomotive model illustrates the complexity of the solved problem and at the same time it has certain limitations. For example, it does not capture the impact of track irregularities in the wheel/rail contact, the angular movements of the bogie frames, longitudinal oscillations of bodies and others. Therefore, a full-complex model of the locomotive was created in the Simpack multibody software. This model is shown in Figure 2.

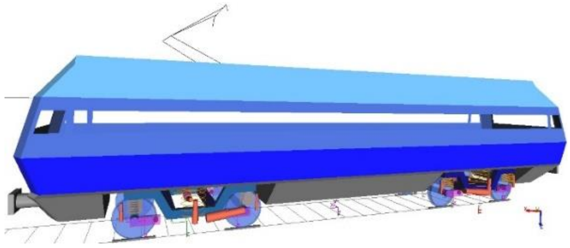

Fig. 2. **Multibody model of the locomotive in the Simpack software**

As there is not defined a particular way to evaluate the ride comfort of the locomotive driver, the research team has decided to adopt the existing method for the presented research purposes. Two methods were chosen, namely, the method according to the ISO 2631 standard [32] and the N_{MV} method N_{MV} according to the EN 12299:2009 standard [29]. These methods were chosen because the EN standard is usually applied for railway vehicles, and it comes from the ISO standard [30; 33; 34]. The ISO standard is a fundamental method for evaluation of vibration effects to a drive body during vehicle running. It consists in a calculation of a modified weighted value of acceleration $a_{rms\text{-}w}$. This value represents a synthetic ride comfort index, and its total value is calculated as follows:

$$a_{rms-w} = \sqrt{a_{x,rms-w}^2 + a_{y,rms-w}^2 + a_{z,rms-w}^2}\ , \qquad (2)$$

where $a_{x,rms-w}$, $a_{y,rms-w}$ and $a_{z,rms-w}$ – weighted average value of acceleration in the third octave band for three axis x, y and z, respectively, m·s^{-2}.

Subsequently, this calculated value of the total weighted acceleration (eq. 1) is compared with the scale in Table 1.

Table 1

Scales for evaluation of the level of ride comfort

Scale according to the ISO standard [32]		**Scale according to the EN standard [29]**	
$a_{rms\text{-}w}$ **[m·s^{-2}]**	**Evaluation**	N_{MV} **value**	**Evaluation**
Lower than 0.315	Comfortable	$N_{MV} < 1.5$	Very comfortable
From 0.315 to 0.63	Slightly uncomfortable	$1.5 \le N_{MV} < 2.5$	Comfortable
From 0.50 to 1.00	Uncomfortable	$2.5 \le N_{MV} < 3.5$	Average comfortable
From 0.80 to 1.60	A lot uncomfortable	$3.5 \le N_{MV} < 4.5$	uncomfortable
From 1.25 to 2.50	Very uncomfortable	$N_{MV} \ge 4.5$	Very uncomfortable
More than 2.00	Extremely uncomfortable	–	

Average comfort calculated by the standard method and marked as N_{MV} quantifies the level of ride comfort according to the EN standard. It is necessary to know accelerations in a longitudinal (x), lateral (y) and vertical (z) direction in five-second intervals. The acceleration values are weighted by the function in a frequency range 0.4 Hz to 100 Hz. The resulting value of the ride comfort index N_{MV} is calculated based on a formulation:

$$N_{MV} = 6 \cdot \sqrt{\left(a_{xP95}^{W_d}\right)^2 + \left(a_{yP95}^{W_d}\right)^2 + \left(a_{zP95}^{W_b}\right)^2}\ , \qquad (3)$$

where $a_{xP95}^{W_d}$, $a_{yP95}^{W_d}$ and $a_{zP95}^{W_b}$ – 95th percentage of the weighted values of accelerations calculated in five-second intervals in three axis x, y and z, respectively, m·s^{-2}.

Finaly, the calculated value of the ride comfort index N_{MV} is compared with the scale for the ride comfort assessment given in Table 1.

Results and discussion

The simulation computations of the locomotive running were performed for chosen conditions. Track irregularities were defined as the power spectral density of irregularities according to the ERRI B176 [35]. The results are discussed for two types of railway tracks defined in combination with two levels of track irregularities and two running speeds:

- A straight railway track, the low and high track quality, running speeds of 80 and 120 km·h^{-1};
- A real track section, the low and high track quality, running speeds of 50 and 80 km·h^{-1}.

It means that the results are shown for eight combinations of track geometries, track qualities and running speeds. It should be mentioned that a locomotive can run on the real track at lower running speeds than on the straight track section due to curvatures of the real railway track geometry. The results of the simulation computations are in a form of numerical values of the $a_{rms\text{-}w}$ acceleration and of the N_{MV} index and they are listed in Table 2. The values $a_{rms\text{-}w}$ accelerations are calculated based on the formulation (2) with the detailed description in the ISO standard [32] and the N_{MV} ride comfort index is calculated based on the formulation (3), which is detailed described in the EN standard [29].

Table 2

Resulting calculated values of ride comfort indices

Track geometry	Track quality	Running speed, km·h^{-1}	ISO 2631 $a_{rms\text{-}w}$, m·s^{-2}	EN 12299:2009 N_{MV} value
Straight track	Low	80	0.197	0.71
		120	0.228	1.37
	High	80	0.121	0.38
		120	0.172	0.59
Real track	Low	50	0.182	0.91
		80	0.217	1.42
	High	50	0.135	0.43
		80	0.198	0.74

These values of ride comfort were calculated in the Simpack software module PostProcessor. An advantage of this software is that it offers for a user to apply the needed weighing functions and filters directly in the PostProcessor user interface at which they correspond to the weighting functions defined in the mentioned standards. As it can be seen, the values accelerations $a_{rms\text{-}w}$ are in the range from 0.121 for the straight track, high quality and the running speed of 80 km·h^{-1}. The highest value of this criterion is 0.228 for the straight track section, low quality and running speed of 120 km·h^{-1}. When the calculated values of the $a_{rms\text{-}w}$ accelerations are compared with the scale in Table 1, it can be seen that all assessed running conditions are evaluated as “Comfortable”. The values of the ride comfort index N_{MV} reached higher values (Table 2) than in the previous case. However, it is because of a different way of calculation of this ride comfort index. This criterion considers different weighting functions and filtering the acceleration signals. The lowest value of the N_{MV} index of 0.38 was reached for the high quality of the straight track and for 80 km·h^{-1}. It is the same as according to the ISO standard. On the other hand, the highest value of 1.42 was calculated also for low quality, for the real track section and also for the running speed of 80 km·h^{-1}. When the calculated values of the N_{MV} index are compared with the scale in Table 1, the ride comfort of the locomotive driver is “Very comfortable” for all cases.

Conclusions

1. Ride comfort of a locomotive driver was evaluated for various running conditions.
2. A multibody model of a locomotive was created in the commercial software. The created model included rigid bodies and viscoelastic couplings.
3. The simulation analyses were aimed at the calculation of the ride comfort indices according to the ISO standard (values $a_{rms\text{-}w}$) and according to the EN standard (ride comfort index N_{MV}). Calculations of ride comfort indices were performed in the Simpack PostProcessor module.

4. The maximal value of the a_{rms-w} was of 0.228 and the maximal value of the N_{MV} index was of 1.42. The achieved results showed that ride comfort of the locomotive driver was for all investigated cases evaluated as “Comfortable” (according to the ISO standard) or as “Very comfortable” (according to the EN standard).

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Author contributions

Conceptualization, J.D., M.B., A.L. and V.I.; methodology, J.D., A.L. and M.B.; software, J.D., M.B., A.L., V.I. and M.B.; validation, J. D. and A.L.; formal analysis, J. D., M.B., A.L and V.I.; investigation, J.D., A.L. and M.B.; data curation, J.D., M.B., V.I. and M.B.; writing – original draft preparation, J.D. and A.L.; writing – review and editing, M.B. and M.B.; visualization, J.D. and V.I.; project administration, J.D. and A.L.; funding acquisition, J.D. and A.L. All authors have read and agreed to the published version of the manuscript.

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