Assessment of Passenger Comfort, Taking into Account Their Position in the Cabin and the Design Features of the Car

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Keywords: Passenger car, flexible floor, mathematical modeling, passenger comfort, anthropometric dummy, unbalanced acceleration, net dose of motion sickness.

Abstract: A method for predicting the comfort level of passengers in an electric train car is proposed, taking into account the design features of the car and the position of passengers in the cabin. The methodology is based on mathematical modeling of the movement of a railway train along real track irregularities. The elastic properties of the supporting structure of the body are taken into account on the basis of the inclusion of a detailed finite element model of the car interior in a solid model of a railway train. In order to clarify the picture of dynamic effects on the passenger, the finite element model of the car is supplemented with finite elements describing the resilient properties of the passenger compartment floor. When assessing the comfort level, an analysis of accelerations obtained on computer models of anthropometric dummies integrated into a finite element calculation model of the body was performed. The mannequins were located in 26 positions in the passenger compartment. Two variants of car models are considered in the work: without taking into account the elasticity of the elements of the passenger compartment and mannequins and with their presence. The level of passenger comfort was assessed according to the criteria of the percentage of passengers experiencing discomfort when driving in a curve and a net dose of motion sickness when modeling the movement of the train along real track irregularities in the range from 20 km/h to the design speed. Comparison of the results obtained by the traditional method and the proposed in the work showed the possibility of data refinement up to 10%.

1 INTRODUCTION

One of the main competitive factors in the passenger transport services market is passenger comfort, the importance of which increases with increasing distances. For passenger rail transportation, improving the level of passenger comfort is a key direction. Traditionally, passenger comfort is understood as an external mechanical effect from vibrations and low-frequency oscillations (CEN 12299 Railway applications — Ride comfort for passengers — Measurement and evaluation, 2009). Thus, the prediction of passenger comfort at the design stage of rolling stock is reduced to determining the level of external influence. The most widely used methods for determining the level of external influence have been mathematical modeling of the movement of rolling stock along real track irregularities.

The traditional approach to modeling the dynamics of rolling stock is to represent the bearing parts and interior elements by a system of absolutely solid bodies (Romain, 2014). In (Ling, 2018; Zhou, 2009), an approach is proposed according to which the bearing parts can be replaced by pliable bodies whose elastic properties are described using the finite element method. The inclusion of pliable bodies in a general mechanical system with solids has been called the "hybrid" method (Kovalev, 2009). The use of the hybrid method makes it possible to increase the prediction accuracy by up to 80%, for bodies with relatively low rigidity in the direction of vibrations.

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In the described approaches, the calculation of passenger comfort is carried out on the basis of data measured on the bearing parts of the car or elements rigidly connected to them. The interior of modern passenger cars is designed taking into account the need to reduce the vibration impact on a person, so the floors of the car can be installed on a special resilient base. The introduction of additional vibration isolation elements in the interior of the cabin is usually not taken into account when studying passenger comfort by traditional methods, which introduces an error in the results of assessing passenger comfort at the design stage and may lead to additional costs for excessive measures to reduce the level of vibration exposure.

The accuracy of the passenger comfort assessment depends on his anthropometric features, posture and location in the passenger compartment (Shorokhov, 2015). At present, modern dynamic models of anthropometric dummies have been developed (Polanco, 2011; Perez, 2010), which can be used to assess the dynamic impact on a person, including on railway transport. In (Rabinovich, 2006), it is proposed to use mathematical biomechanical models in which the human body is represented by one or more elements having mass and combined elastic-dissipative bonds to assess a person's reaction to external mechanical impact. In railway practice, computer models of anthropometric dummies are used to assess passenger comfort and vehicle safety (Antipin, 2017; Antipin, 2017; Antipin, 2018; Bondarenko, 2021), presented by a set of elements connected by means of hinges, capable of accurately reproducing the behavior of the human body under mechanical stress and measuring forces, displacements and accelerations in various parts of the body.

2 MATERIALS AND METHODS

The paper considers several approaches to obtaining initial data for calculating comfort indicators: on the load-bearing elements of the body, on the interior elements of the cabin (floor, seats), on anthropometric models of dummies.

As comfort criteria, it is proposed to use the percentage of passengers experiencing discomfort when moving in the curve - P_{CT} and the net dose of motion sickness - NR. The percentage of passengers experiencing discomfort P_{CT} was calculated in accordance with the requirements of the CEN 12299 standard (CEN 12299 Railway applications — Ride comfort for passengers — Measurement and evaluation, 2009):

$$P_{CT} = (A \cdot |\ddot{y}_{ls}|_{max} + B \cdot |\dddot{y}_{ls}|_{max} - C) + D \cdot \dot{\varphi}_{ls\,max} \quad (1)$$

Where:

$\ddot{y}_{ls}$– lateral acceleration of the body, m/s ^{2};

$\dddot{y}_{ls}\dddot{y}_{\mathrm{ls}}$yls – the rate of increase of acceleration of the body in the transverse direction, m/s ^{3};

$\dot{\varphi}_{ls}$ – body tilt speed, rad/s;

A, *B*, *C*, *D*, *E are* constants accepted in accordance with (CEN 12299 Railway applications — Ride comfort for passengers — Measurement and evaluation, 2009).

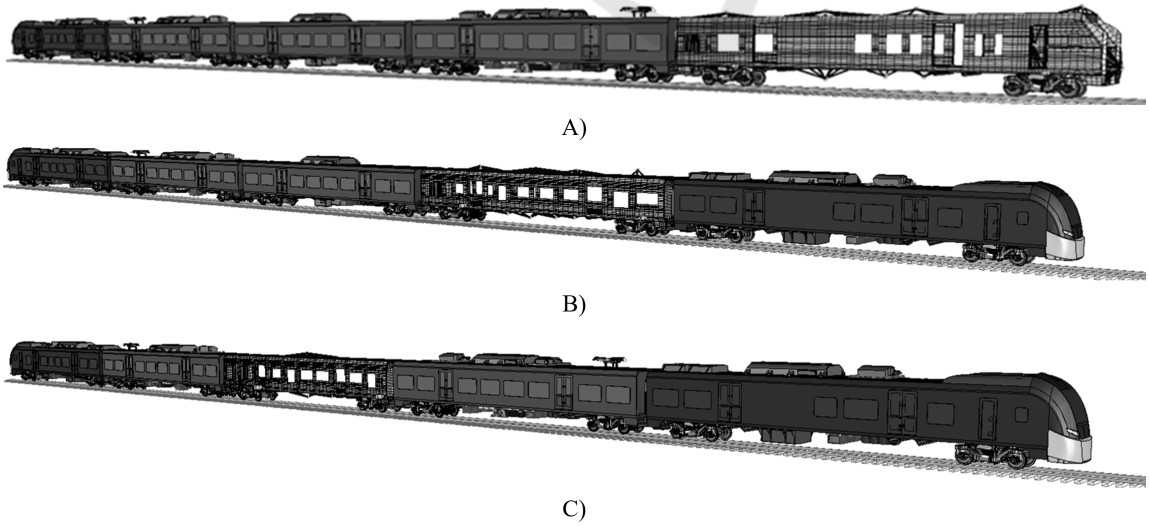

Figure 1: Hybrid dynamic models of an electric train taking into account the elastic properties of the body: a – the head car; b – a trailer car with a pantograph; c – a trailer intermediate car.

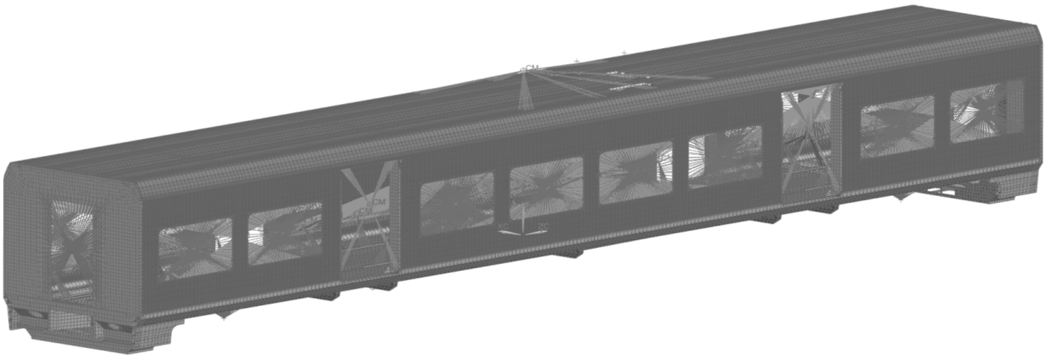

Figure 2: Finite element model of the trailer car body.

The net dose of motion sickness *NR* was calculated on the basis of a motion model that takes into account lateral vibrations and body rotation (Persson, 2011):

$$NR = \beta_0 + (\beta_1 \cdot a_{y\,wf} + \beta_2 \cdot a_{rx\,wf}^2) \cdot \sqrt{t} \quad (2)$$

where β_0 , β_1 – coefficients taken in accordance with the model describing the movement (Persson, 2011);

$a_{y\,wf}$, $a_{rx\,wf}$ is the root-mean-square frequency-weighted acceleration for the horizontal transverse direction and rotation relative to the longitudinal axis.

The values of the motion sickness criterion were evaluated only for passengers in the "sitting" position on a scale from 0 to 3, where 0 – "no symptoms", 3 – "moderate nausea".

A comparative analysis of approaches to obtaining initial data for calculating comfort indicators was carried out on the basis of a dynamic hybrid model of a five-car coupling of a promising domestic electric train ES2G "Lastochka" (Mitrakov, 2019) (Fig. 1).

The coupling model was developed in the Universal Mechanism software package using the subsystem method, according to which cars represent hybrid subsystems of the first level, consisting of subsystems of the second level: absolutely solid subsystems describing the running gear – "bogies ", and the bodies of cars in the form of elastic subsystems – "body".

The load-bearing elements of the car body were described using the finite element method. The extruded aluminum profile of the bodies and the floor of the cars were represented by three and four node shell elements with five nodal degrees of freedom. The mounted and internal equipment of the car was modeled by placing special elements in the centers of weights that allow assigning mass-inertia characteristics to the nodal point (Fig. 2). The subsystems of the running parts of the trolley car are completely similar to those described in (Mitrakov, 2020).

The model verification procedure was carried out by comparing the dynamic indicators obtained during the simulation with the data of full-scale running tests of the ES2G electric train. The following indicators were considered in the verification: frame forces, vertical and horizontal transverse accelerations of the body at floor level in the pivot zone, indicators of vertical dynamics of the first stage of spring suspension and smoothness of travel in vertical and horizontal directions. The maximum discrepancy was revealed for the indicator of vertical accelerations of the body of the motor head car - 18.6%, which is an acceptable value when analyzing the dynamic loading of the body and allows the possibility of using the developed computer model to assess comfort indicators (Mitrakov, 2020).

Increasing the accuracy of comfort forecasting was achieved by including a resilient floor model in the developed model. The description of the connections between the car bodies and the floor elements in the model was carried out by 1-d elements of the "Cbush" type. The properties of these elements were calculated as equivalent elastic-dissipative characteristics of wooden beams and rubber gaskets in the floor supports and were set along the three axes of the car. A solid-state model Dummy Hybrid was used to determine comfort indicators on models of anthropometric dummies, describing a man with anthropometric parameters corresponding to the 50th percentile (Hybrid III 50th Male Dummy. Humanetics Innovative Solutions, https: // humanetics.humaneticsgroup.com; Kobishchanov, 2016). Models of dummies were considered in two positions "sitting" and "standing". Solid models of car seats were additionally introduced to accommodate seated dummies. The dummies were placed in the

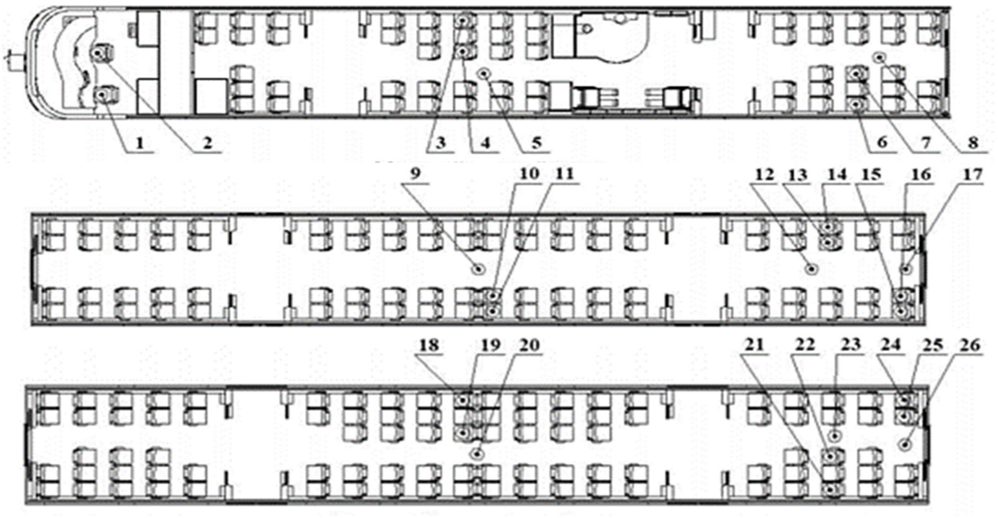

Figure 3: The placement of the dummies in the car compartments: a – motor head car; b – trailed intermediate car with a pantograph; c – trailed intermediate.
1, 2 – models of a dummy in the "sitting in the chair" position of the driver and assistant;
3, 6, 11, 14, 15, 18, 21, 24 - models of a dummy in the "sitting in the chair" position of a passenger at the window;
4, 7, 10, 13, 16, 19, 22, 25 - models of a dummy in the "sitting in the chair" position of the passenger at the aisle;
5, 8, 9, 12, 17, 20, 23, 26 - models of a dummy in the "standing" position of a passenger in the aisle.

first three cars of the five-car coupling at the most characteristic points. The total number of dummies is 26, of which 8 are in the standing position, 18 are in the sitting position. The placement of the dummies in the car compartments is shown in Fig. 3.

An example of the location of dummies in the "body" subsystem is shown in Figure 4.

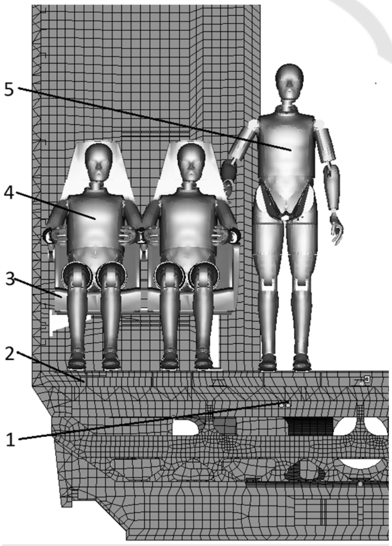

Figure 4: The placement of the dummies in the interior of the car body: 1 - the supporting structure of the car body; 2 – elastic elements of the floor support; 3- solid-state elements of the seat; 4 – dummies in the "sitting" position; 5 - dummies in the "standing" position.

Modeling of rolling stock movement was carried out on sections containing straight and curved sections of the track with radii of 350 m, 600 m, 1000 m. The speed of movement was taken from 20 km/h to the maximum allowed on the considered section of the path.

3 RESULTS AND DISCUSSION

Based on the simulation results, the values of the percentage of passengers experiencing discomfort when moving in the curve were calculated - P_{CT} and the net dose of motion sickness – NR. The values of the indicators were determined on the load-bearing elements of the body; the supporting surfaces of the floor and passenger seats; anthropometric dummies.

On the load-bearing structure of the body, the worst values of comfort indicators among seated passengers are observed when the motor head car is moving with the implementation of the maximum unbalanced acceleration at position 1 (Fig. 3a). The value of the discomfort index in the P_{CT} curve was 19.9%, the net dose of motion sickness NR was 1.4. The best indicators of passenger comfort are observed in the trailed intermediate car at position 19 (Fig. 3c), the value of P_{CT} was 16.2%, and the value of NR was 1.24. Comfort indicators for standing passengers depend to a lesser extent on the location of the car in the train. The lowest values of P_{CT} were found in the trailed intermediate car for position 20 - 28.7%, and the highest for position 26 – 30.5%. The analysis of comfort indicators revealed their dependence on the level of unbalanced acceleration. The best comfort indicators were observed with equilibrium motion in curves of a larger radius. With a decrease in the radius of the curve, there was an increase in lateral acceleration and a deterioration in passenger comfort.

Figures 5, 6 show the relative deviation of the values of P_{CT} and *NR*, obtained taking into account the elastic support of the floor of the car and anthropometric dummies, relative to the values on the metal structure of the body for the positions indicated in Figure 3.

The analysis of the results showed that taking into account the support of the passenger compartment floor on elastic elements, as well as the registration of accelerations on seats and dummies leads to a deviation of comfort indicators relative to the values on the supporting structure of the body:

- decrease in the P_{CT} indicator measured at the floor level by 7-10 %;
- decrease in the P_{CT} indicator measured at the passenger seat level by 1-3 %;
- increase in the P_{CT} indicator measured on the dummy body by 5-10 %;
- decrease in the *NR* indicator measured at the passenger seat level by 2.3-3 %;
- increase in the *NR* indicator measured on the dummy body by 3.8-10%.

Taking into account the design features of the compartment, as well as measuring accelerations on the support surface of the passenger seat, lead to a

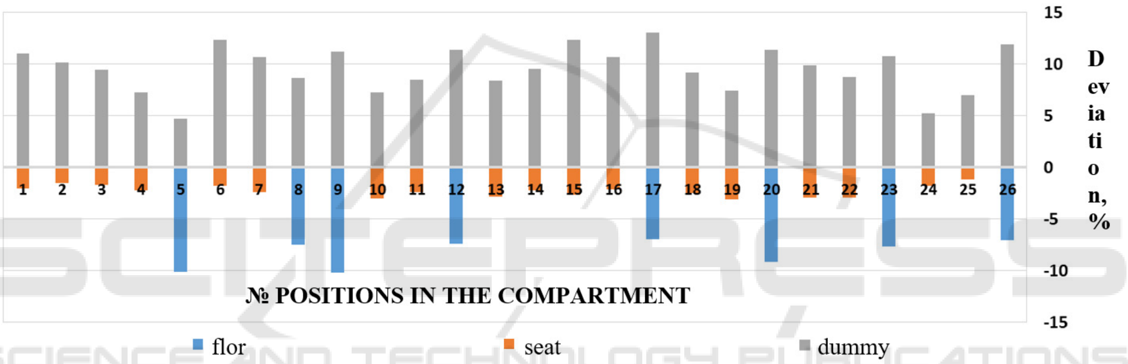

Figure 5: Deviation of the P_{CT} indicator with different measurement approaches, relative to the values on the supporting structure of the body.

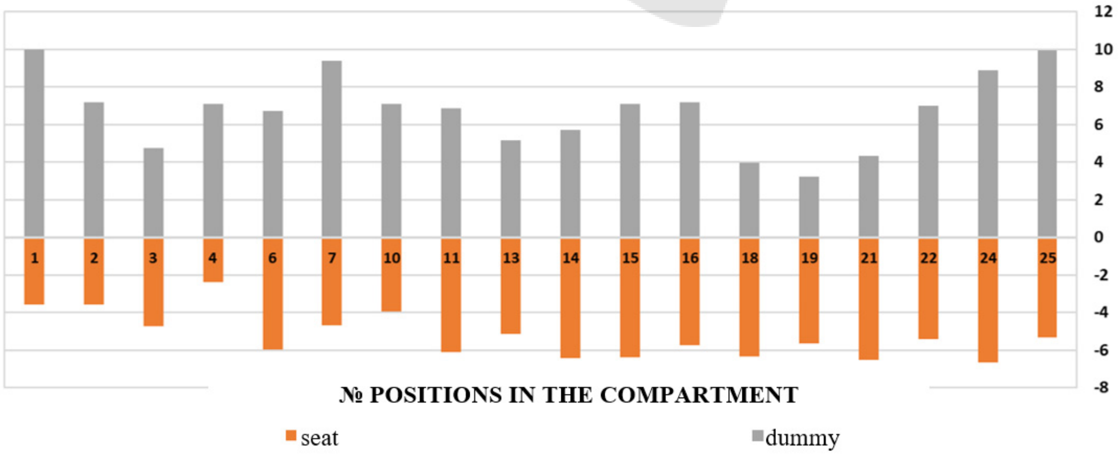

Figure 6: Deviation of the *NR* indicator with different measurement approaches, relative to the values on the supporting structure of the body.

decrease in the analyzed indicators by 1-10%, depending on the location of the check-in point. At the same time, the indicators obtained on the basis of accelerations registered on the body of the dummy exceed the values obtained on the metal structure of the body by 3.8 – 10%, which is explained by the removal of the data registration point from the floor level of the car and from the axis of rotation of the body when it is tilted in curves.

4 CONCLUSIONS

The results obtained indicate the expediency of taking into account the design features of the passenger compartment and passenger accommodation in it when analyzing the comfort level. The proposed methodology, unlike traditional approaches, allows you to predict the level of passenger comfort in various areas of the passenger compartment, which makes it possible to justify constructive solutions aimed at increasing its level in local areas. The results of the work can be applied in the development of systems for active damping of floor elements and passenger seats to increase passenger comfort, design of new types of rolling stock with low natural frequency of car bodies.

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