SPECIAL

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Evaluation of the vibration impacts in the transport infrastructure environment

Abstract This paper presents the problem of vibrations generated by the transport infrastructure. Two aspects of influence on the environment are presented: the harmful influence of vibration on people, and effect on engineering objects. Content of work concerns the identification of dynamical influences, planning of studies, building of models, and validation of their parameters. Simulation methods, based on conducting the experimental pilot studies each time, for the purpose of analysis were presented. In this document, particular attention was paid to the identification of vibration's sources, propagation and evaluation of the vibrations' impact caused by transport means, and operated transport infrastructure. This paper illustrates steps in the research within the analysis, summarizes the existing evaluation methods, and indicates an effective evaluation way for the study area and transparent interpretation level of dynamic influences.

Abbreviations

acc	As a subscript, the acceptable value of the limit specified or calculated on standard's basis
a_k	Prognosed or measured in experimental investigation value of acceleration in k-direction (m/s^2)
a_{kw}	Weighted value of vibration acceleration in k-direction (m/s^2)
D	Analyzed set of impact directions, $D = \{x, y, z\}$
EO	Engineering object (e.g., building structure)
f	Center frequency of ith one-third octave band (Hz)
F_t	Vector of one-third octave frequency bands, dim $F_t = 1 \times n$, where $n = 30$ or $n = 31$
FEM	Finite element method
FIT	Fit coefficient of output characteristics obtained from the model and the real object
FPE	Akaike's final prediction error
G-F	Phenomena of ground–foundation contact area
i	Number of ith one-third octave center frequency band
k	Impact direction/propagation of mechanical vibrations selected from a set of three directions of the Cartesian coordinate system
K_{AIC}	Akaike's information criterion

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MC	Measuring cross section
MP	Measuring point
PSO	Potential of vibration influence hazard
SI	System identification method
SIMO	Single input multiple output model, or version SISO—with single output
T	Duration of the measurement (s)
VDV_k	Vibration dose value, measured or recorded in k-direction (m/s$^{1.75}$)
VLF	Vibration load factor
VS	Paraseismic vibration source
W_i	Weighted coefficient of ith one-third octave band
W-R	Phenomena of wheel–road contact area

1 Introduction

Progressive intensity of traffic with complex structure by type in urban areas and its daily traffic variation generate an extension of the traffic peak hours. Expansion of urban areas and modernization of transport infrastructure in city centers create local high congestion of heavy vehicles on city streets [14,15]. These vehicles provide supply to technical backgrounds of construction sites or remove construction spoil, which belongs to the production waste category group. In such cases, temporary changes in traffic movement are introduced, and transport routes to landfills are traced. In the case of people transport, there are new form of communication solutions for replacement or support existing public transport lines with new, more efficient media. The main goal of this work was the formulation of a method for the analysis of the effects of the existing traffic roads modernization in urban areas, on vibration level of infrastructural elements, with the special attention paid to:

– changes in distance between traffic routes and neighboring engineering structures,
– changes in daily traffic congestion on arterial roads that, temporarily, take over traffic within the area prior to modernization,
– changes in land ownership in the surroundings of the new or modernized investment that have direct influence in the impact zone.

Elastic ground vibrations caused by controlled or uncontrolled human operational activities (e.g., transport-borne vibration) give results in paraseismic form waves. The vibrations coming from the operating elements of the transport infrastructure and means of transportation, propagated by the ground into the environment, in selected time intervals can be classified as paraseismic, random, stationary—ergodic—process. The motivation of this work was the lack of clear method of research results' evaluation and assessment of impacts.

Dynamic phenomena in the vehicle wheel–road system generate kinematic enforcement transferred to the infrastructure and migrated to the environment [1–5,12]. Selected analyses are prepared for studying interactions and predictions, based on the propagation path analysis, for vibrations originating from transport infrastructure to the zone of influence. It requires individual examination of each communication route, by appearing on the modes of transport with specific dynamical signature of each transport means [5,7,11]. Sources of impacts, interaction points, and flow directions of dynamic enforcement signal are shown in Fig. 1.

Considering the complexity of impacts, it is essential to create interdisciplinary study teams, composed of specialists from transportation, construction mechanics, ground mechanics, or environmental protection fields in order to prepare reliable expert reports on the impact of transport means on the local environment. The mechanism of vibration's generation (e.g., effect of contact phenomena) and transmission in urban area was discussed in many bibliographical sources [1,2,4–9,11,12].

For detailed discussion, tension analysis and spectral evaluation of vibration for engineering objects are carried out [16,17]. Evaluation and assessment methods, using FEM software, are based on the detailed analysis in the microlevel [13]. The problem arises when it is necessary to prepare global analysis, for the entire transport route, such as whole street in urban agglomeration. Specialists from non-vibration impact phenomena sectors are not able to determine the potential risk based on detailed test results. For this purpose, guidelines for the construction of Dynamic Transport Influences Evaluation System (DTIES) were provided. This system is based on the use of phenomenological models in dynamic occurrences examination, such as the propagation of paraseismic vibrations [8]. Several assumptions were established, meaningly simplifying the process of model preparation and the stage of its "tuning." The effects of simplified models introduction in the analysis and the impact of simplification on the quality of results were investigated.
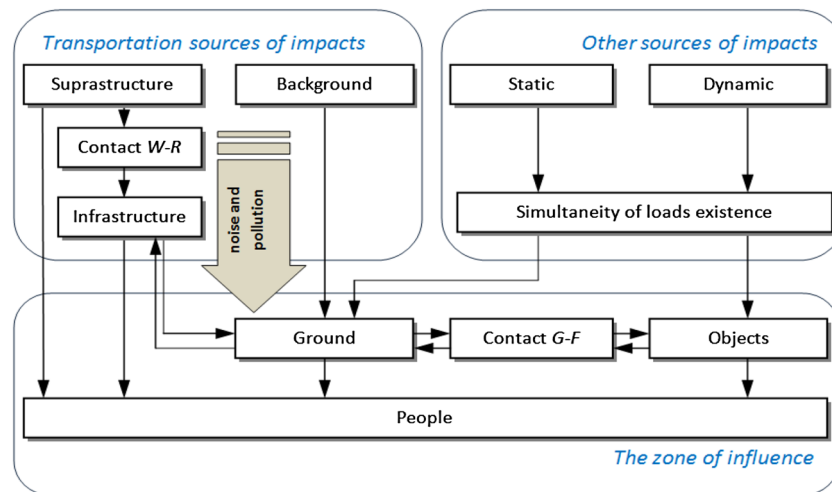
Fig. 1 Sources and directions of dynamic interactions [8]

2 Methodology of simulation

The main purpose of this work was quick and clear assessment of projected dynamic effects caused by existing transport infrastructure modification or the modernization of transport route. The task was performed by analysis based on experiment and simulation studies. Particular attention (called objective function) was focused on dynamical impact effects on people, staying temporarily or long term in the influence zone. The objective function is achieved through the construction of DTIES in MATLAB environment. System functionality allows for multi-criteria dynamic dimensioning of forecasted impacts in the analyzed area, after introduction of a new transport medium. Solution of the problem involves experimental studies, selection and apply of appropriate methods of simulation in predicting the dynamic influences, generated by the parts of transport infrastructure. Figure 2 shows the overall proceeding algorithms used in DTIES.

The first step is orderly registration area of impacts, taking into account the sources of vibration—VS; engineering objects—EO, located in the zone of interaction; and three-dimensional terrain digitization, including a symbolic description of the vibration area, taking into account the general location of the sources of vibration and engineering objects. This step is necessary to enter numeric values describing the geometric position of objects and distance. In other studies, the matrix of digitization area was used to build the visualization system environment (in Simulink VRML [8,10]). This is not a trivial step, but in this case a high level of detail is not required. This stage is also the designation of the measuring cross sections—MC and target measuring points—MP, for measurement and assessment of impacts. The next step is the experimental pilot studies. They are divided into the study of dynamic background, with registration in selected test-points waveforms of vibration acceleration, caused by ground movement without the heavy vehicles in the movement structure; and study of the dominant vibration sources in the existing type of traffic organization. Experimental studies were carried out for selected points—MP, but in the case of registration of waveforms generated by the dominant transport vibration source, in minimum two reference points on the ground level. They served an additional designation of competent dynamic characteristics of the transfer function of vibration through the ground. In reasonable cases, after the registration of existing vibration sources, for example when designing the new transport medium in the research, the registration of additional sources representing a new medium in similar conditions were carried out. In order to obtain high efficiency of testing in time domain, modeling based on system identification method whenever possible were used [20,21]. Method of systems identification was used, to determine the parameters of the model the phenomenon of vibration transmission. In order to test hypotheses about the correct selection of model structures, Akaike's information criteria were used in the study (1–3).

$$K_{\text{AIC}} = N \ln \hat{\sigma}_{sp}^2 + 2p \tag{1}$$

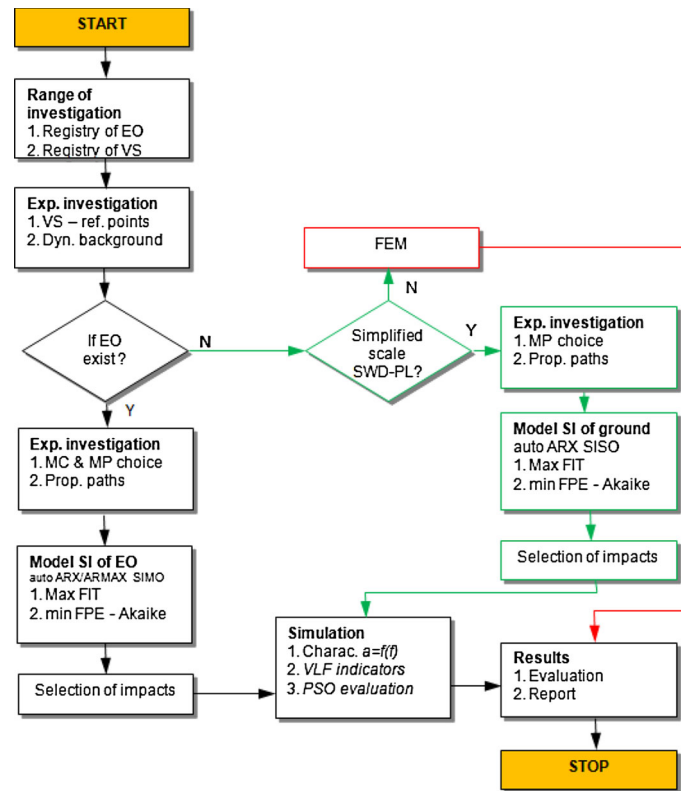$$K_{\text{FPE}} = \hat{\sigma}_{sp}^2 \left(\frac{N + (p+1)}{N - (p+1)} \right) \tag{2}$$

Fig. 2 General algorithm used in DTIES [8]

$$\mathrm{FIT} = \left(1 - \frac{\|y - y_e\|}{\|y_- \bar{y}\|}\right) 100 \tag{3}$$

Akaike's information criterion; FPE is Akaike's final prediction error; FIT is fit factor; N is the number of analyzed signal samples; p is model row; $\hat{\sigma}_{sp}^2$ is experimentally estimated prediction error variance of the order p; y is the value of the signal at the output of the object obtained from the measurement; $\bar{y}$ is the average value of the output signal obtained from the measurement object; y_e is the value of the signal at the output of the estimated object model.

The next item was to conduct the analysis of signals amplitude in frequency domain. In the case of impacts assessment for the nonexistent objects structure (in the draft stage), first test gave the answer whether analyzed objects were comply with requirements of simplified method of impacts assessment, based on the assessment scale of dynamic impacts—SWD according to [18]. If so, theoretical harmful influence was evaluated on the basis of determining the characteristics of the vibration transmissibility through the ground (SISO model), by obtaining a maximum acceleration vector for the selected terrain points, regarding the terms used in standard, describing the position of the measuring point—"… on foundation, in the ground level, from the side of vibration source" [18]. The structure's response in the ground level is checked from the direction of vibration source, and next, the results are compared to the values accepted by criteria. In this method are built automated, simplified models of vibrations transmission processes, with the consideration of the real dynamic characteristics. For this purpose in predictions, additional experimental measurements were taken for selected measuring points. Selection of the optimal model type "black box" was performed on the basis of optimization criteria mentioned earlier [8,9,20,21]. There were two variants of boxes considered (SIMO and SISO), based on ARX and ARMAX models. Detailed comparison of the results of these models was included in [6,9]. For not fully identified problems of evaluation the dynamical phenomena, connected with the absence of real physical object, for example in the draft stage, it was not possible to complete the analysis of the influence on the people staying at this object. Figure 3 shows particular solution for SIMO model, which is used to obtain results for selected propagation path.

The process of identifying the parameters for the selected propagation path was conducted in accordance with accepted principles of identifying of the real objects. Vibration acceleration waveform was taken as
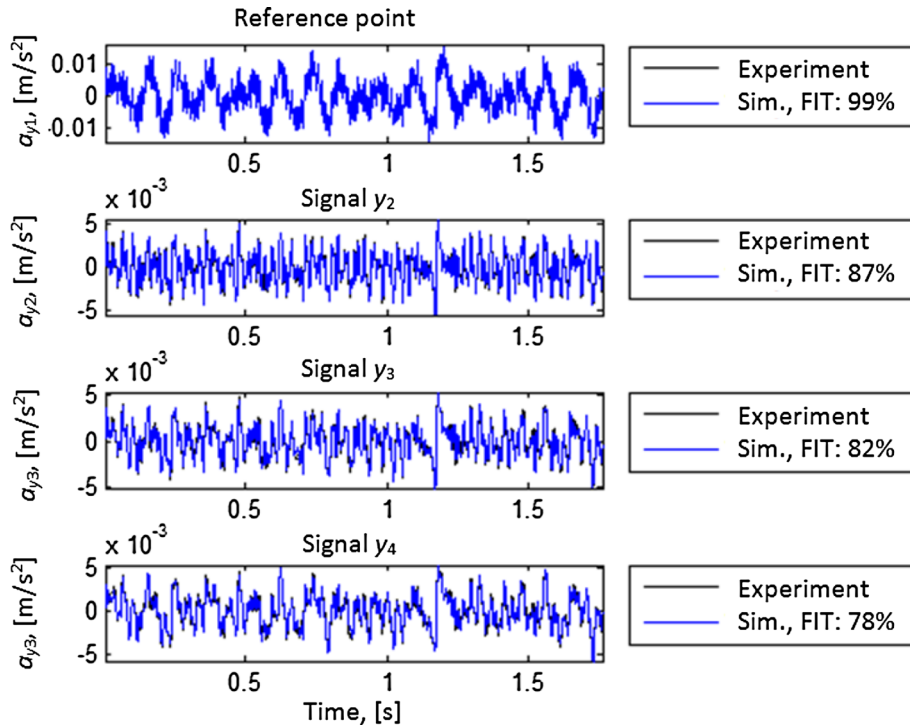
Fig. 3 Detailed studies using an SIMO model [6]

an input signal, measured at the input of the propagation path. Because the structure of the model depends on the state of the inputs and outputs, and does not depend on random components, the model used for the analysis was linear, parametric, stochastic, and stationary. In this class type, ARMAX (*Auto Regressive Moving Average with eXogenous input*) models fulfill expectations. In order to minimize errors generated during tests, when modeling using the method ARMAX, the optimization of the selection of coefficients n_a, n_b, n_c, n_k was made. These coefficients are, respectively, defined by row of polynomials A, B, C, and the phase shift between input and output. Thus, they influence the row and the resulting error polynomial model. Optimization of the model structure was performed as iteratively repeated simulation. This optimization was based on the minimalization of the Akaike's information criterion (AIC) and minimalization of final prediction error (FPE), during the simultaneous change in polynomials describing the model and while maintaining highest possible value of fitting coefficient (FIT). Similarly to the model ARX, during examining the zero-pole plots, unstable models were rejected. They appeared mainly in higher order of polynomials, and were caused the transition of estimated pole on the unstable side.

Construction of MATLAB software that allows to perform iterative analysis of models showed significant relationships between the model row, optimizing the use of the adopted criteria, and the complexity of the signal extortions and responses. In the next step, an attempt was made to improve the ratio of the maximum fit. Based on the real condition, the nonlinear behavior characteristics of real building structures were the result of wear phenomena and micro impacts in the contact zones. Recorded signals were averaged, and next the newly created transmissibility dependencies were checked. Therefore, a transformation from the time domain to the frequency domain and then decomposition of signals were performed. Next parameters of dynamical models iteratively were determined, regard to transmission of individual frequency bands. In practice, one of the results presented in the article (Fig. 3) was obtained using method described above.

$$A(q) = 1 + 1.261\,q^{-1} + 2.363\,q^{-2} + 1.256\,q^{-3} + 0.9922\,q^{-4}$$
$$B(q) = 4.866\,q^{-1} - 2.858\,q^{-2} + 4.848\,q^{-3}$$
$$C(q) = 1 + 3.272\,q^{-1} + 5.074\,q^{-2} + 4.9\,q^{-3} + 2.86\,q^{-4} + 0.7385\,q^{-5}$$

For engineering objects not fulfilling the criteria for simplified scale (SWD), modeling using FEM was necessary [13]. The accelerations of vibration obtained at the measuring end points were used as the input

waveforms for models of objects built in FEM environment and for verification. Kinematic extortion model was adopted in the form of vibration acceleration waveform components. Extortion directed to all nodes from ground level to a depth of foundations was taken into account at the same time, from the appropriate direction of vibration source. Studies have been conducted with one acceleration component and for all components simultaneously. For existing objects, first stage was the appropriate choice of measuring cross sections and verification of previously selected points location. Then, waveforms of accelerations at selected points were recorded, using a multi-channel signal acquisition hardware, under the condition of simultaneous registration of vibration in whole measuring cross section. On the basis of the specially processed signals, using FIT, AIC, and FPE optimization criterion [21], and the method of system identification (SI), appropriate SIMO models of existing engineering objects were determined, and simulation studies were conducted. Regardless of the method of conducting simulation studies, after the model validation and verification, the frequency domain characteristics were obtained, indicators of the vector of vibration load factors for objects and people were calculated (VLF[1]) , and then, the potential of harmful impacts (PSO) was determined.

3 Method of impact assessment based on indicators

The first step was conducted for the calculation of vibration load factor in general description, which is calculated by the following formula using the acceleration amplitudes (aa) for each analyzed direction of vibrations and frequency in one-third octave bands (4):

$$\underset{f \in F_t}{\forall} \underset{k \in D}{\forall} \text{VLF}_{aak} = \frac{a_k(f)}{a_{k\text{acc}}(f)} \tag{4}$$

where acceptable values can be calculated as follows:

$$a_k \text{acc} = \begin{cases} a_{k\_\text{rms}}\text{—for people} \\ a_{k\_\text{max}}\text{—for buildings} \end{cases} \tag{5}$$

a_{k_rms}, human perceptibility limit of vibrations in the direction of k; r.m.s. acceleration value—according to the standard [19]; a_{k_max}, acceptable acceleration of vibration value, defines the lower limit taking into account the dynamic influences on the structure of building in the k direction, according to standard [18].

The next step was introduction of the indicator based on weighted value of vibration acceleration (6):

$$\begin{cases} a_{kw} = \sqrt{\sum_{i=1}^{n}(W_i a_{ki}(t))^2} \\ a_{kw} = \sqrt{\frac{1}{T}\int_0^T a_{kw}^2(t)\text{d}t} \end{cases} \tag{6}$$

A more advanced form of the indicator is based on the weighted values, used in order to determine the logarithmic vibration dose load factor, for a known time interval T and the direction of impact k, shown in (7).

$$\text{VLF}_{kwa} = 20\log\frac{a_{kw}}{a_{kw\_\text{acc}}} = 20\log\frac{\sqrt{\frac{1}{T}\int_0^T \left(\sum_{i=1}^n (W_i a_{ki}(t))^2\right)\text{d}t}}{\sqrt{\frac{1}{T}\int_0^T \left(\sum_{i=1}^n (W_i a_{ki\_\text{acc}}(t))^2\right)\text{d}t}} \tag{7}$$

The vibration loading of people, caused by vibration dose value (VDV), can be calculated on the basis of formula (8):

$$\text{VDV}_k = \sqrt[4]{\int_0^T (a_{kw}^4(t))\text{d}t} \tag{8}$$

An indicator based on the weighted value, used in order to determine the load factor based on logarithmic vibration dose value, for a known time interval T and the impact of direction—k, can be calculated as in (9):

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[1] Designation adopted in the work [8] and used in publications.

$$\text{VLF}_{kvdv} = 20\log\frac{\text{VDV}_k}{\text{VDV}_{k\text{acc}}} = 20\log\frac{\sqrt[4]{\int_0^T \left(\sqrt{\sum_{i=1}^n (W_i a_{ki}(t))^2}\right)^4 \mathrm{d}t}}{\sqrt[4]{\int_0^T \left(\sqrt{\sum_{i=1}^n (W_i a_{ki\_\text{acc}}(t))^2}\right)^4 \mathrm{d}t}} \tag{9}$$

This indicator allows to evaluate the risk of harmful exposition to vibrations, from the point of view of vibration dose value (8), for residents remaining in the building exposed to vibrations. All obtained results for people staying in buildings were acceptable. In further studies we found, that this indicator is relevant only in case of vibration occuring driver seat in the vehicle, instead of vibration influence in engineering objects.

The next stage of research was the introduction to analyze the value of vibration acceleration derivative with respect to time. It was another indicator based on signal amplitude. This value is interpreted as "rate of change in acceleration" or known as *jerk*. Proper waveforms were obtained by derivative of experimentally recorded accelerations with respect to time (10):

$$j_k(t) = \frac{\mathrm{d}\ddot{x}_k(t)}{\mathrm{d}t} = \begin{cases} \frac{\mathrm{d}a_x(t)}{\mathrm{d}t} \\ \frac{\mathrm{d}a_y(t)}{\mathrm{d}t} \\ \frac{\mathrm{d}a_z(t)}{\mathrm{d}t} \end{cases} \tag{10}$$

For the selected ith one-third octave band and selected direction—k, we get:

$$j_{ki} = 2\Pi f_i a_{ki} \tag{11}$$

VLF based on "jerk" is a function of wave direction (k), frequency (f_i), measuring point number, measuring cross section, and engineering object number.

$$\underset{f\in F}{\forall} \text{VLF}_{\text{jerk}} = \frac{j_k(f)}{j_{k\_\text{acc}}(f)} \tag{12}$$

Similarly introduced equivalent for displacement value, in order to estimation the new load factor:

$$\begin{cases} x_k(t) = \int_0^T \left(\int_0^T \ddot{x}_k(t)\mathrm{d}t\right)\mathrm{d}t \\ x_{ki} = \frac{a_{ki}}{(2\Pi f_i)^2} \end{cases} \tag{13}$$

The next step in conducting the analysis was the introduction of quantities characterizing the vibration energy, carried out by the paraseismic waves. For each direction of vibration impact, energy (E) for the vibration acceleration signal of continuous time is described in accordance with Eq. (14) based on the [21]:

$$\begin{cases} E_x = \int\limits_{-\infty}^{\infty} a_x^2(t)\mathrm{d}t \\ E_y = \int\limits_{-\infty}^{\infty} a_y^2(t)\mathrm{d}t \\ E_z = \int\limits_{-\infty}^{\infty} a_z^2(t)\mathrm{d}t \end{cases} \tag{14}$$

Considering the above equations, a new indicator (15) which characterizes vibrations energy load can be calculated:

$$\underset{f\in F_t}{\forall} \underset{k\in D}{\forall} \text{VLF}_{ke} = 10\log\frac{E_{km}}{E_{kp}} \tag{15}$$

where for the discrete-time: E_{kp} acceptable vibration energy, calculated from limit of vibrations perception for human organism, E_{km} energy of vibrations resulting from measurement or prediction (14).

Studies on the behavior of the above indicators allowed to draw the following conclusion. During the analysis of low-frequency transmission, indicator based on the displacement criterion responded fastest, for high frequencies and for accoustical band, indicator obtained from the "jerk" value demonstrated faster reaction.

Table 1 Scale of the *PSO*—developed in accordance with the requirement of the standard [6,18]. (Color figure online)

	Indicator level, [dB]								
	-20,0	-6,0	-3,0	0,0	3,0	6,0	12,0	18,0	20,0
Operating rooms									
Hospitals / day									
Hospitals, sanatoriums / night									
Flats / day									
Flats / night									
Offices, schools									
Workshops, garages & mech.									
	0,1	0,5	0,7	1,0	1,4	2,0	4,0	8,0	10,0
	Module of amplitude ratio								

The next stage of evaluation the vibration load factors was creating global indicators. To achieve this objective, process for determining indicators for all measuring points in all measurement cross sections considered in the analyzed area was automated. The harmful impacts potential (PSO) was defined as the value uniquely characterized by the status of dynamic influences, generated by the means of transport, propagated to the environment. Scale of this can be calculated through the appropriate validation of impacts—considering the reference to the limits described in international legislative standards [6,7,16,17]. In order to increase the transparency of evaluation results, a new concept was introduced in the PSO classification. That allowed for categorizing the overall evaluation of dynamic interactions in three hazard levels: unacceptable, warning, and permitted. Established three generalized levels of the potential (16) are:

$$\text{PSO} = \begin{cases} 0, & \text{permitted— for } VLF \quad [\text{dB}] < 0 \\ 1, & \text{warning— for } 0 \leq VLF \quad [\text{dB}] < L_A \\ 2, & \text{unacceptable— for } L_A \leq VLF \quad [\text{dB}] \end{cases} \tag{16}$$

where L_A represents the upper limit of acceptable level, PSO $= 0$ represents state, when every measured values are below the limits (for human—vibration perceptibility threshold, or for the building—the minimum limit of perceptibility of dynamic impacts for the structure [18,19]); PSO $= 1$ represents state, when every measured values are between limit and acceptable value (upper limit of vibration—see Table 1); PSO $= 2$—when measured values are crossing the limits.

Acceptable level depends on the suitable limit in the adopted measurement conditions, such as dependence of EO destination, when it is located in the area of dynamic influences. The main assumption of impact evaluation methods was to determine the general point of view in a global scale, on selected from the environment many detailed data points.

For the evaluation of the results, detailed assessment structure at the four-level scale: global, local, macro, micro was presented in [6–8]. To this scale, appropriate set of color maps was prepared, for generated characteristics (user-defined colormap option in MATLAB). It allowed for immediate interpretation of research results, as well as for clear evaluation of impacts.

In terms of the presentation results of research from the system, detailed results of the following levels were assumed:

– global scale (the entire area being analyzed, e.g., all the buildings on the whole street or all the buildings of one type),
– local scale (one engineering object of the analyzed objects group),
– macroanalysis (for several measuring points belonging to one measuring cross section containing several points, e.g., on different floors in selected building),
– microscale—detailed consideration of a single point (for example, one measuring point on the selected floor in the building).

It is also more clear, legible, and easier for the recipient to interpret the test results. Particularly useful is the information on a global level. As it is clear from the interviews conducted among the population, people want in the first phase to acquire information on whether the modernization of the transport environment will affect the housing conditions. In the first phase information, people want to know the result presented in logical notation, by getting: yes-impacts will increase or not. Other scales provide information of more and more detailed level, as in the diagnosis procedures.

The principle of group selection calculation results of any VLF, for the need of each level, can be described as follows:

$$\text{VLF} = \begin{cases} \forall_{f \in F_t} \forall_{k \in D} \exists_{np \in M} \exists_{npp \in N} \exists_{eo \in O} \text{VLF}(f)_{eo,npp,np,k} \xrightarrow{\text{scale}} \text{micro} \\ \forall_{f \in F_t} \forall_{k \in D} \forall_{np \in M} \exists_{npp \in N} \exists_{eo \in O} \text{VLF}(f)_{eo,npp,np,k} \xrightarrow{\text{scale}} \text{macro} \\ \forall_{f \in F_t} \forall_{k \in D} \forall_{np \in M} \forall_{npp \in N} \exists_{eo \in O} \text{VLF}(f)_{eo,npp,np,k} \xrightarrow{\text{scale}} \text{local} \\ \forall_{f \in F_t} \forall_{k \in D} \forall_{np \in M} \forall_{npp \in N} \forall_{eo \in O} \text{VLF}(f)_{eo,npp,np,k} \xrightarrow{\text{scale}} \text{global} \end{cases} \quad (17)$$

where np, measuring point number, belongs to the set of all digitized measuring points M, contained in the matrix of terrain digitization $\mathbf{M_{DT}}$; npp, number of the measuring cross section, belongs to the set of all declared measuring sections N, contained in the matrix $\mathbf{M_{DT}}$ included in the matrix concurrency $\mathbf{M_{CD}}$, comprising one or more measurement points; eo, selected to evaluate the number of engineering object, comprising one or more measuring cross sections npp, belonging to set of objects covered by the area of impact—O.
The presentation of PSO is based on the following principles (17).

$$\text{PSO} = \begin{cases} \forall_{f \in F_t} \exists_{np \in M} \exists_{npp \in N} \exists_{eo \in O} \max_{k} \left(\text{PSO}(f)_{eo,npp,np,k} \right) \xrightarrow{\text{scale}} \text{micro} \\ \forall_{f \in F_t} \exists_{npp \in N} \exists_{eo \in O} \max_{np} \left(\max_{k} \left(\text{PSO}(f)_{eo,npp,np,k} \right) \right) \xrightarrow{\text{scale}} \text{macro} \\ \forall_{f \in F_t} \exists_{eo \in O} \max_{npp} \left(\max_{np} \left(\max_{k} \left(\text{PSO}(f)_{eo,npp,np,k} \right) \right) \right) \xrightarrow{\text{scale}} \text{local} \\ \forall_{f \in F_t} \max_{eo} \left(\max_{npp} \left(\max_{np} \left(\max_{k} \left(\text{PSO}(f)_{eo,npp,np,k} \right) \right) \right) \right) \xrightarrow{\text{scale}} \text{global} \end{cases} \quad (18)$$

Declaration of PSO values (18), with the four-level scales, allows the selection of correct indicators despite the large group of obtained solutions. This is particularly important if immediate receipt of the information about the current state of interactions in the analyzed area is needed and allows to give clear answers in the absence of exceedances of the limit values, without the need for detailed analysis of all the results.

4 Results

This section shows examples of the research results obtained by the operation of the system TDIES. The results of experimental research are shown in Figs. 4, 5, and 6, for the analysis of real street situation. Results were submitted on a global scale, for selected nine measuring cross sections (order numbers 1–28), in which there were only four-storey engineering objects. The analyzed residential buildings were old that were built in the early twentieth century. The state of maintenance of buildings pointed to the need to prepare research of vibration influence. They did not have vibroisolation systems, and the distance to the nearest source of vibration was less than 10 m (including lateral and vertical position of metro tube). The main reason of tests was the introduction of a new metro line in this area. Additional vibration sources were trams and single carriageway street having four lanes. Structure of the traffic consisted of cars, buses, and vans. The publication [8] shows the whole range of considered studies. In this work, the comparison of the overall evaluation of vibration for 44 objects modeled by FEM, and the results of analysis performed with simplified black-box method were performed. There were also the result comparison obtained using both methods.

In this case, it was necessary to analyze only the existing situation, and there was no need for forecasting and simulation research. The actual results of the vibration acceleration in lateral direction registered in situ were used to calculate the VLF. Figure 4 shows the amplitude VLF factor, obtained for nine measuring cross sections belonging to one street. The value of the vibration acceleration was assessed in transverse direction to the road axis. ISO standards and local Polish standards suggest considering the vibration impact on engineering objects in the range of 1–100 Hz, because in this area there is a real threat to the structure. ISO standard suggests a larger values of the analyzed vibration frequency. Normative values, ranges, and limits were adopted on the basis of existing legislation in force in Poland and the European Union. Insofar, analysis was performed, which was justified by better matching coefficients FIT (3) obtained for models SISO/SIMO. For the purposes of modeling using FEM analysis, ranges 1–512 Hz were used for better identification of acoustic reactions of windows in the building.
As it is shown above, trivial index based on an assessment of acceleration (4) shows any alarming symptoms.
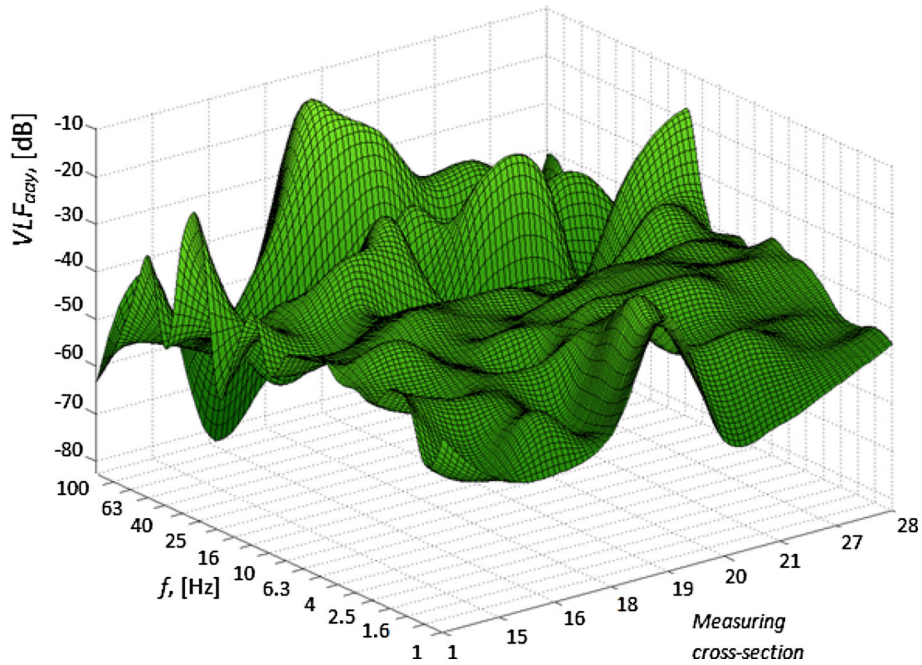
Fig. 4 Logarithmic amplitude index for the selected measuring sections located on one street; *y* direction, the source of vibration—the cumulative impacts of all transport modes at the same time
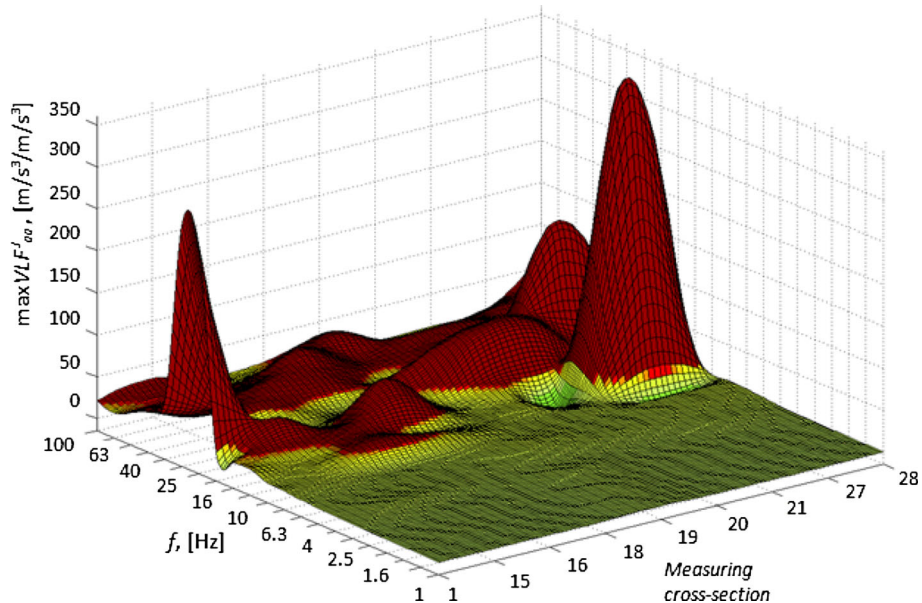

Fig. 5 Global VLF factor calculated for maximum change in the derivative of acceleration, the four-storey buildings located on the selected street

Figure 5 shows the global values of VLF factor based on maximum change in the derivative of acceleration, for the four-storey buildings located on the selected street. Three directions (x, y, z) were analyzed at the same time. Main source of vibration was the metro line. Actual accelerations were analyzed, with later obtained derivative, in order to obtain the jerk, which were used to calculate the VLF.

As it is shown above, exploitation of underground lines (especially shallowly located underground railway), can cause acoustical response of glass and wall surfaces and structures.

Figure 6 shows the maximum values of the logarithmic factor of vibration energy load of engineering structure objects. Results are shown for the chosen measuring cross sections, containing nine buildings on the selected
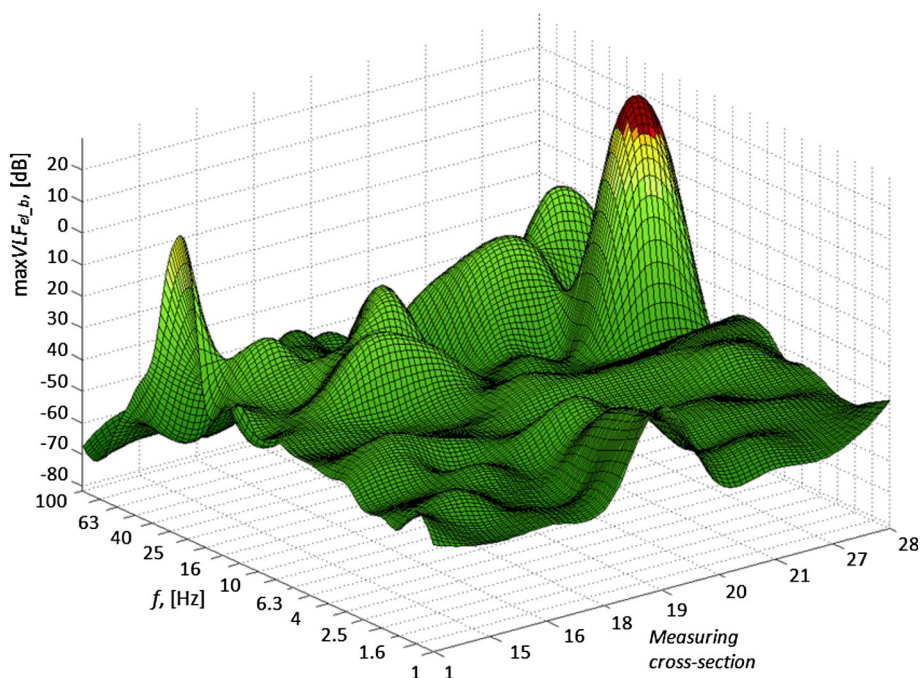
Fig. 6 Maximum values of the logarithmic factor of vibration energy load for the building structures

street. Horizontal directions (x, y) of interactions are analyzed. The source of the paraseismic vibrations was the cumulative impact of all transport modes.

Analysis of a global scale, shown in Fig. 6, demonstrated a risk of exceeding the safety limit (PSO = 2), caused by the energy of vibration impact in the 27 and 28 measurement cross sections for frequencies in the range 20–40 Hz. An appropriate safety factor for buildings with the value 0.7 was used in the analysis (marked b), which is in accordance in Regulation [15]. Impacts source came from ground-borne (paraseismic) mechanical vibrations. Physical meaning exhibits the greatest vibration energy directed to the objects in the area. The vibrations in this frequency range significantly degrade the comfort of staying in the rooms [19]. The observed level of vibrations does not affect the possibility of damage of the objects structure. The vibrations are below the lower limit, when taking into account the dynamic building interactions [18].

5 Concluding remarks

The presented method improves the carrying out assessments of dynamic interactions in surroundings of transport areas. Generating results for vibration load factors, divided into a fourstage scale of details, allows for the knowledge of issues for both: the experts' analysis and for the sectors not related to dynamic interactions. The fourstage scale in surface domain, covering different parts of the analyzed area (micro, macro, local, and global level), helps in the analysis of the results.

The use of VLF indicators, to evaluate the dynamic interactions generated by the exploited vehicles, introduces a new quality in the field of impact analysis. Individual selection of indicators for vibration impact evaluation on people or objects allows to develop multi-criteria approaches for measuring vibration in the environment.

The construction of a dynamic impact system is a very complex issue, which requires an arbitrary evaluation of the situation. In the case of the existing structures in good technical condition, new structures and projected structures, the most accurate results of simulation calculations come from the FEM method. It allows to indicate accurately all the impacts in any points of the finite element mesh. This high accuracy is required for structures exposed to vibration levels which exceed or are close to the acceptable level. However, it has one disadvantage: the necessity of long-term calculations and a relatively difficult model calibration, which, in the case of real engineering structures, presents a significant impediment in studies.

For such structures, the method of "black boxes" representing dynamic behaviors with the use of system identification method seems more appropriate. Both methods are compatible with the ISO standards. This

method gives the answer in one , precisely chosen point, which is sufficient from the point of view of the general evaluation of vibration impact on humans. "Black-box" methods did not allow to analyze vibration distribution in the region under study. For this purpose, better solution gives FEM-based methods. But at the end, for estimation influence on people according to Standard [19], we should use only one point (with maximum rms acceleration value on the floor). "Black-box" method indicates vibration in one point, but this seems to be sufficient especially for engineering objects, during the simplified evaluation of ground vibrations in the ground level.

Accoustical reaction of glass and wall surfaces and structures is easier to detect using VLF based on the jerk. As it is shown in Fig. 5, the indicators based on jerk react much faster for higher frequencies; thus, it can be concluded with increased risk of acoustic response, when limit values are exceeded. Adequately, VLF indicators based on the displacement can be used for strength calculations for the supporting structures of objects, in combination with Huber's hypothesis for steel and the Coulomb–Mohr hypothesis for concrete structures.

References

1. Adamczyk, J., Targosz, J.: Vibroisolation of automobile road elements. In: Proceedings of the 1st IC-SCCE, Athens (2005)
2. Ciesielski, R., Maciąg, E.: Road vibrations and their effect on buildings, p. 248. WKŁ, Warsaw (1990)
3. Chudzikiewicz, A., et al.: Monitoring of railway vehicle-track system dynamic, monograph in polish (Monitorowanie stanu ukladu dynamicznego pojazd szynowy-tor). WUoTPH, Warsaw (2012). ISBN 978-83-7814-050-4
4. Chudzikiewicz, A.: Symbolic modeling in simulation research of rail vehicle. Arch. Transp. **9**(3–4), 15–25 (1998)
5. Chudzikiewicz, A., Droździel, J., Sowiński, B.: Mathematical model of track settlement caused by dry friction. Arch Transp. **21**(3–4), 25–38 (2009)
6. Korzeb, J., et al.: Research project no. N N509 501 838, entitled: Evaluation of the transportation routes impacts for people staying in their zone of influence, report in polish (System oceny wpływu szlaków komunikacyjnych na ludzi przebywających w strefie ich oddziaływania) Faculty of Transport, Warsaw University of Technology, Warsaw (2010/12)
7. Korzeb, J.: Construction of an evaluation system for dynamic impacts on transportation investment impact zones. In: Proceedings of 4th IC-EpsMsO, vol. 1, pp. 165–170. Patras University Press, Athens. ISBN 978-960-98941-7-3 (2011)
8. Korzeb, J.: Prediction of selected dynamic impacts in the transport infrastructure impact zone, monograph in polish (Predykcja wybranych oddziaływań dynamicznych w strefie wpływu infrastruktury transportowej), Scientific Papers of Warsaw University of Technology, Transport Series, No. 90, ISSN 1230–9265, ISBN 978-83-7814-111-2, WUoTPH, Warsaw (2013)
9. Korzeb, J., Ilczuk, P.: The use of parametric models in simulation the propagation of transport borne vibration (in polish Zastosowanie modeli parametrycznych w badaniach symulacyjnych propagacji drgań transportowych), Logistics (logistyka), 4/2011, CD/pp. 428–435
10. Korzeb, J., Ilczuk, P.: The use of VRML environment for visualization of selected dynamic interactions in urban agglomeration. (in polish Wykorzystanie środowiska VRML dla potrzeb wizualizacji wybranych oddziaływań dynamicznych w aglomeracji miejskiej). Warsaw University of Technology, Scientific Papers, a series of Transport, Z. 98, OWPW, Warszawa 2013r., s. 301–310
11. Nader, M., Korzeb, J.: Dynamic interactions in the transport infrastructure environment. Vib. Phys. Syst. **XXV**. Ed. by Cempel, C., Dobry, M. Poznan University of Technology, pp. 459–468, ISBN 978-83-89333-43-8. Comprint, Poznan (2012)
12. Nader, M., Różowicz, J., Korzeb, J.: Simulating investigations of traffic generated vibrations influence on people staying in buildings. In: Proceedings of 36th INTER-NOISE, CD, Istanbul Turkey (2007)
13. Rakowski, G., Kacprzyk, Z.: Finite Elements Method in Construction Mechanics. Publisher WPW, Warsaw (2005)
14. Regulation of Council of Ministers of 9 November 2010. About the projects likely to have significant effects on the environment, OJ Item No. 213, pos. 1397
15. Regulation of Infrastructure Minister, 17th of June 2011, Concerning the technical conditions to be met by underground building facilities and their location. Not. by European Commission, OJ It. No. 144, pos 859
16. Standard ISO 4866(1990–1996), Mechanical vibration and shock—vibration of fixed structures—guidelines for the measurement of vibrations and evaluation of their effects on structures
17. Standard ISO 14837–1(2005): Mechanical vibration and shock—ground borne mechanical vibration arising from rail systems
18. Standard PN-85/B-02170 (1985) Evaluation of vibration transmitted through the ground on buildings
19. Standard PN-88/B-02171 (1988) Evaluation of the impact of vibration on people in buildings
20. Sőderstrőm, T., Stoica, P.: System Identification. Publisher PWN, Warsaw, ISBN 83-0112158 (1997)
21. Zieliński, T.P.: Digital signal processing. From theory to applications. (in polish Cyfrowe przetwarzanie sygnałów. Od teorii do zastosowań). WKiŁ, ISBN 978-83-206-1640-8, Warszawa 2009, s. 832