Method of reconstructing dynamic load characteristics for durability test of heavy semitrailer under different road conditions

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Arkadiusz Czarnuch[a,c,*], Marek Stembalski[b], Tomasz Szydłowski[a], Damian Batory[a]

[a]Łódź University of Technology, ul. Stefanowskiego 1/15, 90-537 Lodz, Poland
[b]Wroclaw University of Technology, ul. Lukasiewicza 5, 50-371 Wroclaw, Poland
[c]Wielton S.A., ul. Rymarkiewicz 6, 98-300 Wielun, Poland

Highlights

- Road data was recorded using real semitrailer with a set of sensors.

- Drive data was created and verified using the road simulator.

- Dynamic load characteristics of different road conditions was made.

- The reconstruction of the road load data conditions was as high as 97%.

- This methodology is valid for accelerated durability test for different road conditions.

Abstract

The aim of the article is to present and validate a methodology for collecting road load data on a vehicle, driving on roads and analysis of a drive data signal under the wheel in the time domain, using FRF (Frequency Response Function) and the MTS 320 eight-poster inertia reacted road simulator. The elaborated drive data, was used to control the actuators forcing the movements of the wheels and the coupling part of the semi-trailer during durability tests. The road tests were carried out by registering physical variables in the time domain, by a set of sensors mounted on a vehicle. The data was collected from roads categorized as motorways, national and local roads. Differences between the variability of the parameters, collected on the roads and the variability of the drive data under the wheel, were determined for the particular types of roads, for loaded and unloaded vehicle. The obtained accuracy of reconstruction of the road load data conditions was as high as 97%. Therefore, the proposed method is suitable for reliable durability tests with use of the road simulator.

Keywords

drive data, road load data, fatigue damage, durability, sensors.

1. Introduction

The durability and reliability of road vehicles depend on many factors. The basic factor is the quality of the manufactured vehicle, which comprises the vehicle structure, the materials used, the material joining technology and the production quality. The second (equally important) factor is the manner and conditions of vehicle use. For example in the case of brake system components, different roads and operating conditions have a significant influence on wear and reliability [22].

In the case of vehicles, their lifetime is specified by the manufacturer, regarding the failure assumption. Paraforos et. al calculated this life time for agriculture vehicle. The authors state that the use of real road profiles is more appropriate than the use of an artificial profile to simulate the fatigue of real vehicles.[15]. On the other hand Kong et. al for this purpose used a particular component of the vehicle, indicating the parameters for which the design of the spring leaf will meet the durability requirements. [10]. Vehicle lifetime is most often expressed by the covered mileage. But mileage, is not the only indicator of fatigue in actual operation [8]. There are many factors which affect durability, besides the kilometres travelled, such as the way the vehicle is driven, whether it is operated in accordance with the manufacturer's guidelines, and varied environment in which the vehicles travel [5].

In order to confirm the assumed lifetime of their products, vehicle producers must carry out durability tests in conditions corresponding to the real ones. Nowadays the durability of manufactured vehicles is tested in two ways. The most popular way, especially for buses and trucks, is to test them on a specially designed proving ground track. This method of durability testing of buses is described and its results are presented by Kepka et al. [9]. In the article it was confirmed, that driving at testing ground around 100,000 [km] can demonstrate 1,000,000 [km] in real conditions. Kosobudzki et al. [12] analysed durability of suspension elements, to estimate their durability limited by the fatigue strength. The authors presented results for short testing distance of 1 [km] at constant speed and conditions emphasizing that this was an initial analysis, which needed confirmation during longer runs under changing road conditions. The other method of durability testing consists of testing of complete vehicles on a road simulator test stand, where the conditions of simulation are based on acquired actual road data, as presented by Chindamo et al. [4]. Vehicle tests on four-post road simulator have been described, by Sharma et al. [19]. The authors described the test of the truck frame on four-post road simulator, presenting the limits of the station with regard to vertical excitation. The eight-poster road simulator was described by Stembalski et al. [20]. Herethe test

station, as well as the data required to carry out durability tests along with the methodology of their collection, was presented

Information about measuring and interpreting road data can be found in [11]. There are different methods of collecting data for the durability test. Imine et al. [6] used a longitudinal profile analyser (LPA) to measure a road profile and estimate the vertical forces acting on the vehicle. A higher-order sliding-mode observer is proposed to estimate the unknown inputs under each wheel. Loprencipe et al. [14] compared generated artificial roads profiles with the real profiles, showing the differences between them due to stationary features. Authors confirms that artificial profiles are useful tool to be used as first approach in interaction analysis between the pavement and the vehicle. Zhao et al. [26] showed that road data can be measured using a smartphone and presented a road surface profile estimating system, accurately predicting road profiles for different vehicles. Allouch et al. [2] also used simple accelerometers to estimate the road conditions. Burger et al. [3] described an approach to derive a virtual road profile based on a replacement tire model. This was an early stage of development, when no physical prototypes were available.

The quality of roads varies considerably between countries. Road parameters are described by factors corresponding to the Power Spectral Density in ISO 8608 [7] or by the IRI factor (International Roughness Index). The road profiles described by ISO 8608 or IRI are for a single track and specific conditions [16]. In reality, plenty of factors have a bearing on the vehicle response. The quality of roads changes over time: roads are damaged or repaired [1]. Vehicle responses can differ between seasons (summer/winter) on the same road. In ref. [13] the effect of speed and road roughness on the variation of the vertical oscillations' frequency of the sprung and unspring masses of a vehicle was determined. Qin et al. [18] analysed different methods for road profile estimation of vehicle system response, however the experimental validation for the whole vehicle was needed. Based on the literature research, it should be stated that road simulators are mostly used for durability tests of passenger cars. Those are mainly four-actuators systems. In the literature, the authors did not find any reports referring to the methodology of testing heavy duty vehicles on eight-posters simulator.

The novelty of this work is collecting road data using heavy duty vehicle and determination of dynamic road load data on eight-poster inertia reacted road simulator. The obtained profiles

were verified based on preliminary tests using known and described object as well as real road conditions. The authors focused on a perfect reconstruction of the drive data using FRF method and the MTS 320 road simulator. The paper presents the impact of the quality of the roads, on which a vehicle travels, on the variation of the recorded parameters. The data was collected directly on the vehicle. For this purpose the vehicle was equipped with sensors recording its behaviour on different roads. Sensors registered four physical quantities: acceleration, displacement, pressure and strain. Roads were categorized into three groups. The first group comprises local roads with poor or damaged asphalt surfaces. The second group includes national roads with an asphalt surface. The third group comprises motorways with a very good asphalt surface. Collected road data was used to elaborate the drive data under the wheel in time domain with use of MTS 320 test bench. The drive data and road load data have been compared to each other in order to determine characteristics of different category of roads. Additionally, verification tests were carried out in order to determine the correctness of reconstructing the course on a road simulator with the use of the speed bump with known geometry. These tests made it possible to compare the generated drive data under the wheel of the vehicle to the actual shape of the speed bump. The diagram of the types of research described in the article is shown in Fig. 1.

2. Data recording methodology and conducted tests

2.1. Description of vehicle

A vehicle for transporting 20' sea containers was used in the research. The vehicle is a 3-axle semitrailer adopted to transport 20' sea containers in two positions. The allowed axle load is 9 [t] and allowed load of the fifth wheel of the tractor is 15 [t]. A view of the vehicle is shown in Fig. 2. The vehicle, weighing about 3 [t], can carry the load (heavy containers) of up to 30 [t].

Fig. 2. Semitrailer for transporting sea containers.
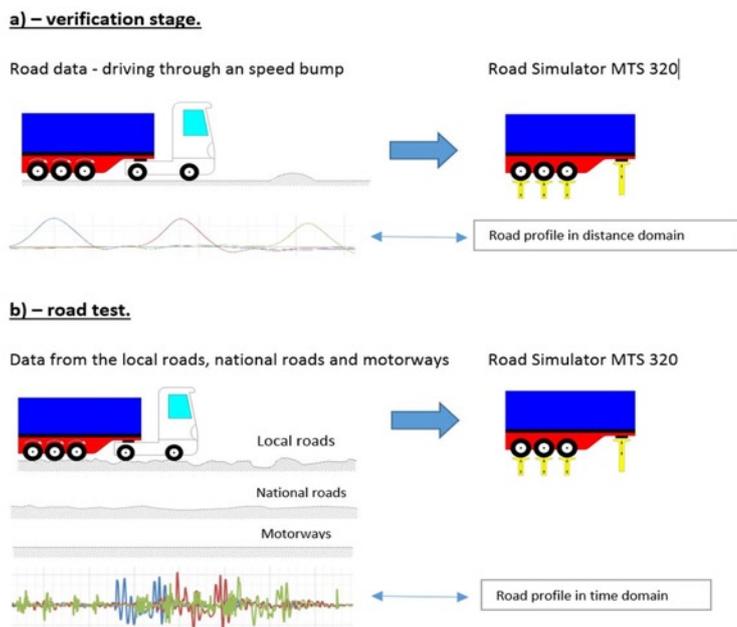
Fig. 1. Diagram of the types of research, a) first stage of verification, b) the second stage of road tests

2.2. Measuring technique

Twenty one sensors were used to measure the behaviour of the trailer on the road. Those data will be the input data for the simulation as road load data. The sensors were located in different places on the vehicle. The sensors, i.e. acceleration, displacement, strain gauges and pressure sensors, were appropriately positioned to measure the vehicle's movement and its suspension on the roads. There were the following sensors:
– 2 accelerometers with measurement range of ±300 [m/s²] with measurement in two axes (4 channels): vertical and horizontal, transverse to the driving axis, located in the front part of the frame;
– 8 accelerometers with measurement range of ±300 [m/s²] with measurement in one vertical axis, located on each axle near the wheels and in the front part of the frame;
– 6 distance sensors with measurement range of ±0.32 [m] located near every wheel, measuring the distance from the axle to the frame;

– 2 half-bridge strain gauges located on the main beams at the places where the cross section changes, measurement in one direction;
– 1 pressure sensor with measurement range of 0-200 [MPa] in the right front air suspension air bag;
– a GPS for recording the position and speed.

The HBM measurement system for data recording, one universal amplifier MX1601 (16 channels) for the accelerometers, one universal amplifier MX840 (8 channels) for the distance and pressure sensors and one strain gauge bridge amplifier MX1615 (16 channels) were used. All the data were recorded by a CX22 data recorder in continuous time with sampling rate of 300 [Hz] using the Catman DAQ software [24].

2.3. Distribution of sensors on vehicle

The locations of the sensors were selected in order to record the behaviour in the crucial places in the vehicle structure – as close as possible to the formation of the forces generated by the road. The locations of the installed sensors are shown in Fig. 3 and Fig. 4.

2.4. Roads selected for reference data collection

Data were collected from public roads in Poland. The routes were selected on the basis of data collected from independent companies using similar vehicles. Table 1, shows the arithmetically averaged reference data acquired from the transport companies, depending on roads type and vehicle mileage.

The vehicle journeys were divided into full load (max Gross Vehicle Weight) and no load runs. The roads on which the vehicle travelled were divided into three groups: local roads, national roads and motorways.
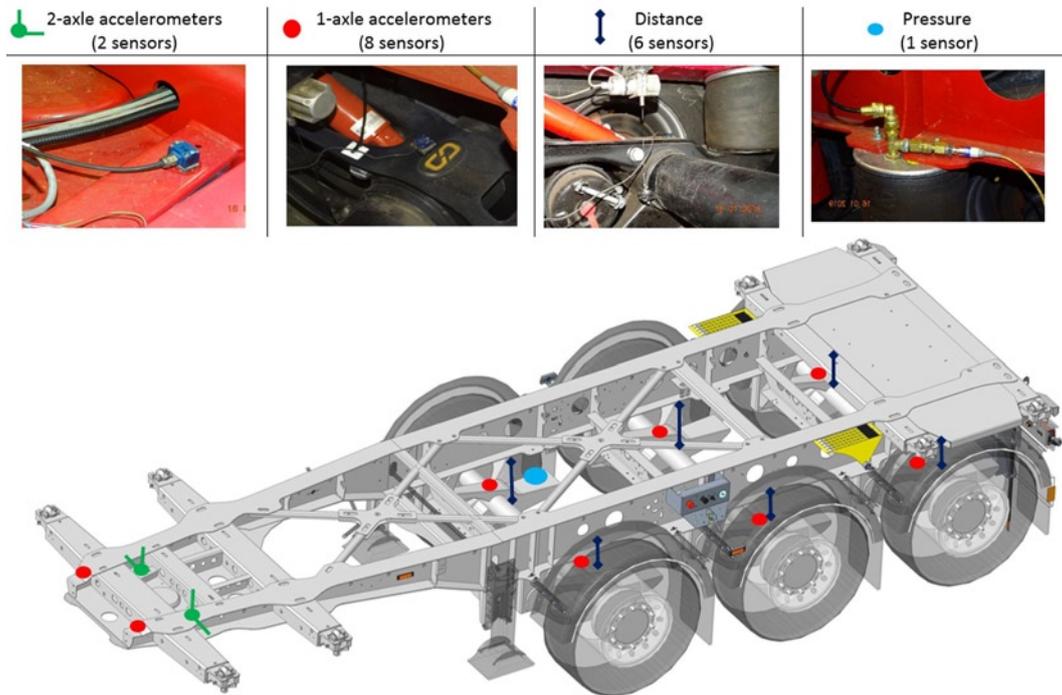
Fig. 3. Locations of installed acceleration, pressure and distance sensors on a trailer
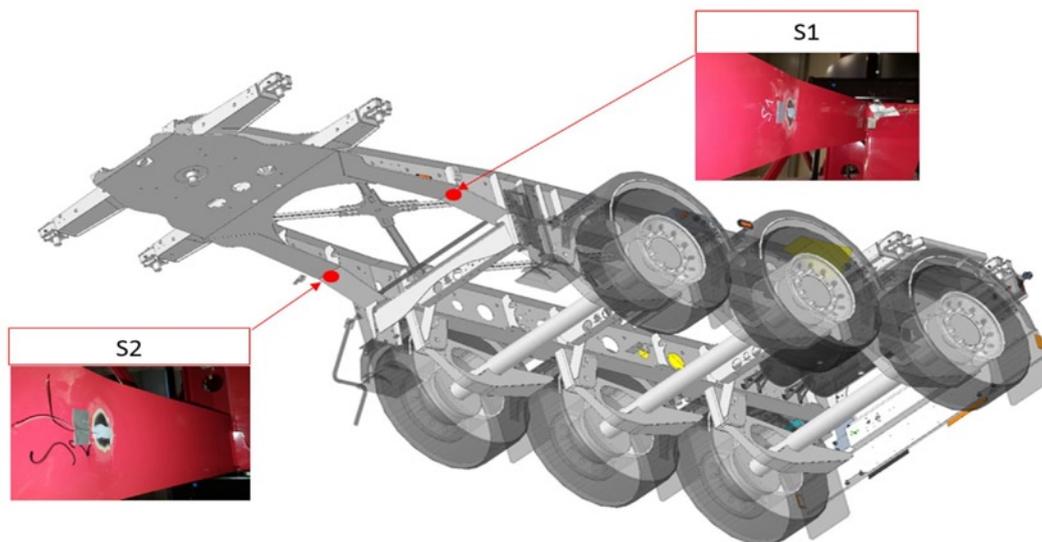
Fig. 4. Locations of one-directional strain gauges

Table 1. *Averaged reference data from clients per year*

Reference data				
	Mileage of loaded trailer		Mileage of unloaded trailer	
	[km]	[%]	[km]	[%]
Total annual mileage	**30 000**	**54 %**	**25 833**	**46 %**
Depending on road type				
Local roads (very rough)	15 167	28 %	13 500	24 %
National roads (rough)	10 167	18 %	8 833	15 %
Motorways roads (smooth)	4 667	8 %	3 500	6 %

Table 2. *Mileages used in test*

Reference data			
		Unloaded trailer [km]	Loaded trailer (load 30 000 kg) [km]
Local roads		142	115
National roads		118	280
Motorways		62	200
	TOTAL [km]	322	595

The data collected from the customers show that this type of vehicle is used in a mixed manner, both loaded and unloaded way. In both cases, journeys on poor road surfaces, classified as local roads, predominate. The reference data (collected from Polish roads) used in the test are presented in table 2.
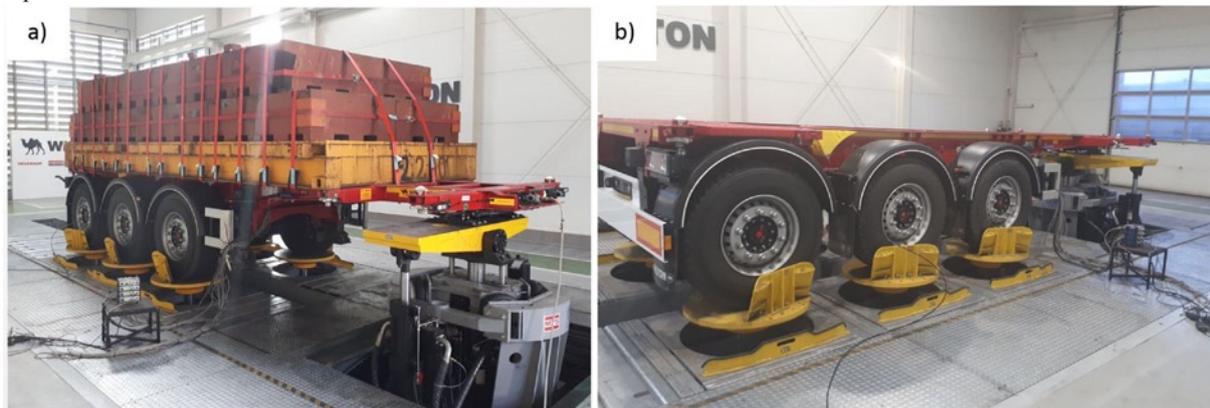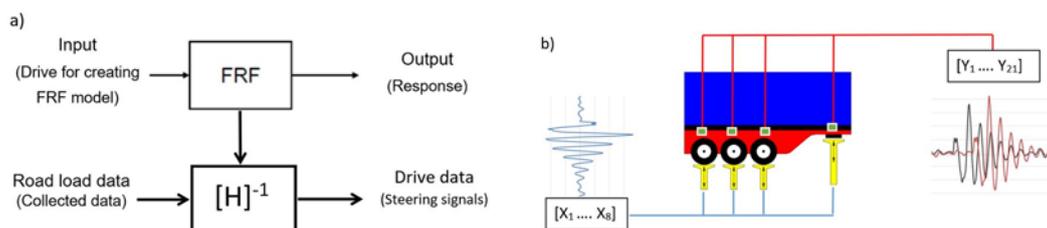
2.5. Methodology of reconstructing the dynamic loads characteristics

The MTS 320 eight-poster road simulator test rig was used to determine (on the basis of the recorded road load data) dynamic characteristics of the drive data under the wheels. The vehicle in two configurations, loaded with 28 [t] and unloaded was installed on the simulator (Fig. 5). The test rig enables to generate input signals (in the form of direct road surface action on the wheels) from collected road data. In the investigated case, the road data, as input data in time domain, (axle displacements, accelerations, pressures and strains) had been collected directly on the vehicle (in crucial places in its structure). The hydraulic cylinders used on the stand can only work in the vertical axis, therefore it is not possible to simulate the maneuvers of braking and acceleration of the vehicle. Moreover, the simulated inputs must not exceed a frequency of 100 [Hz].

The MTS RPC software enables to create a system model in the form of transmittance. The sensors were used in the same configuration as on the road to determine the FRF at each of the frequencies. FRF relates the output of a vibrating system to the input, as described and validated by Zhang et al. [25]. To generate the matrix [H] the inputs are the movements of the rig actuators and the outputs are the responses of the transducers, as shown in *Fig. 6a*. To generate the drive data signals, the inputs data are collected from road data. Finally during the simulation output signals are the responses from the transducers installed on the vehicle.

$$H(f) = \frac{G_{yx}(f)}{G_{xx}(f)} = \frac{CSD}{ASD} \quad (1)$$

where:
CSD – cross spectral density at each frequency, proportional to the power between the input signal and the output signal;
ASD – auto spectral density at each frequency, proportional to the input signal.

Fig. 5. Vehicle installed on MTS Road Simulator: a) loaded trailer; b) unloaded trailer

Fig. 6. Schematic illustration of input-FRF-output

When the model was created it became possible to reconstruct the drive data signal under each wheel in time domain, solely on the basis of values recorded by the sensors mounted on the vehicle, Fig. 6b. The displacement of the wheel-road contact point was determined by multiplying the signals collected from the road by the inverse of matrix H.

$$\begin{bmatrix} x_1 \\ \vdots \\ x_8 \end{bmatrix} = [H]^{-1} \begin{bmatrix} y_1 \\ \vdots \\ y_{21} \end{bmatrix} \qquad (2)$$

where:

x_{1-8} – drive signals under each wheel;
y_{1-21} – the road data response.

2.6. Initial verification tests.

In bench tests, the actual conditions are reconstructed by means of loads and forcing the test vehicle to move. Simplifications are often used to simulate real conditions on a test stand. An example is a rotating wheel of a vehicle that is stationary while carrying out durability tests on stands intended for this purpose. In the first stage various physical quantities were registered while driving over a speed bump. The artificial speed bump in the shape of a segment of a circle with a radius of R = 800 [mm] was used for the tests (the shape of the speed bump was related to the 60 [mm] high speed bumps commonly used, especially on access roads). The speed bump was placed on a paved road in one line for two wheels, so that the speed bump was taken by each of the axles at the same time. Fig. 7, shows a cross-section of the speed bump and the actual appearance.

The speed bump was driven through using a set, a 2-axle truck tractor and a 3-axle semi-trailer. The tests were performed for different speeds from 11 to 25 [km/h] in two variants for an unloaded semi-trailer and a trailer with a load of 28 [t]. The speed was kept constant while driving over speed bump.

After passing the speed bump, the vehicle was placed on the MTS 320 road simulator test stand, used for durability tests of vehicles with a coupling part simulating a truck tractor [20]. The parameters of the stand were adjusted to the tested product in terms of dimensions and mass. Then, the correctness of the mapping of the given shape of the speed bump on the test stand was determined.

3. Results of measurements and discussion

3.1. The verification test results

Based on the registered data, the control signals were recreated for each speed of passing the speed bump. Fig. 8 shows examples of reconstruction the physical quantities, by the road simulator. The acceleration, displacement and pressure signals for the first right wheel for the pass at 11,5 [km/h] for unloaded trailer are presented. The given

Table 3. The level of reconstruction of the signals based on The RMS

Unloaded				
	11,5 [km/h]	15,1 [km/h]	19,7 [km/h]	24,1 [km/h]
Average Acceleration on the axles [%]	93	97	99	98
Average distance on the axles [%]	93	95	98	97
Average pressure on the axles [%]	92	92	97	98

Loaded				
	11,2 [km/h]	15,8 [km/h]	20,5 [km/h]	22,5 [km/h]
Average Acceleration on the axles [%]	98	98	96	98
Average distance on the axles [%]	98	98	97	98
Average pressure on the axles [%]	95	95	95	96
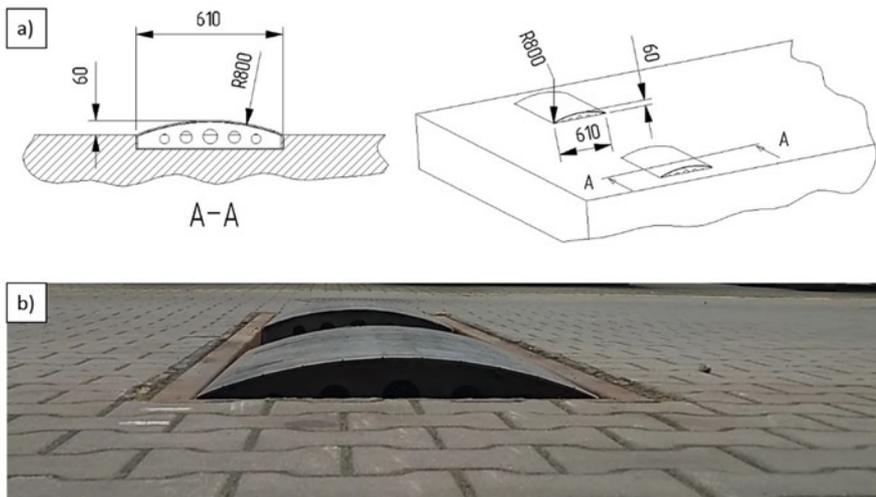
Fig. 7. Speed bump used to test: a) dimensions, b) view of the speed bump
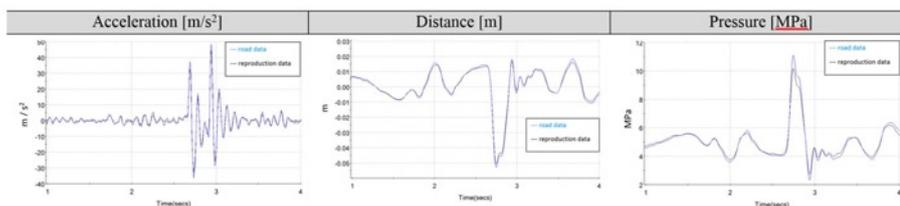
Fig. 8. Reconstruction of the physical quantities

signal was reconstructed in 97% in terms of the root mean square of the signal collected from the path to the root mean square of the signal mapped at the MTS station.

Table 3. shows the percentage difference between the RMS value of the real signal and the signal generated at the MTS stand for all test runs. Analysing the results of the verification tests the obtained reconstruction varies from 87% to 98% regarding the RMS value . The excitations under the wheel of the vehicle, that were generated by the road simulator, were also compared. The comparison of the waveforms in the distance domain with the actual shape of the speed bump is presented in the Fig. 9. The diagram shows the movement of the cylinder under the right front wheel for the runs at different speeds with the unloaded and loaded vehicle.

Analysing the plot on the Fig. 9, it is visible that the course of the actuator movement under the wheel does not fully reflect the shape of the speed bump. For the unloaded semitrailer the reconstruction of the shape depends to a greater extent on the speed. Actuator displacement in comparison to the actual obstacle height for the lowest speed was on the same level, whereas for the highest speed, the displacement was overestimated by 11%. In the case of the loaded semi-

a)

RIGHT FRONT WHEEL - TEST ROUTE WITH AN UNLOADED TRAILER

Speed [km/h] — 11,5 — 15,1 — 19,7 — 24,1 — Road profile - - Theoretical axle shift

b)

RIGHT FRONT WHEEL - TEST ROUTE WITH AN LOADED TRAILER

Speed [km/h] — 11,2 — 15,8 — 20,5 — 22,5 — Road profile - - Theoretical axle shift
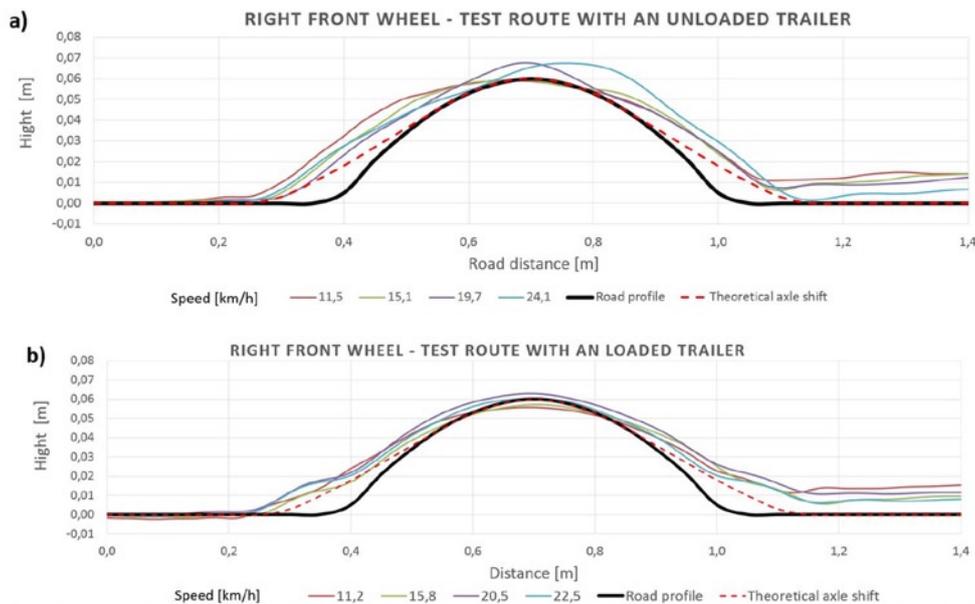
Fig. 9. Drive data under the wheel in comparison to real shape of the speed bump: a) unloaded, b) loaded trailer

trailer, the underestimation of 5% was observed and the speed did not have a significant effect on the actuator movement under the wheels. The greater width at the base of the profile of the speed bump, obtained from the test runs, result from the radii of the wheel and the tire. Since the point of contact of the wheel with the speed bump is shifted in front of the axle, the change in height under the axle does not correspond to the actual profile for both, running up and leaving the obstacle (see fig. 9 dashed line – theoretical axle shift assuming constant radius of the tire). Considering the remaining parameters, the reconstruction of changes in the displacement or acceleration while passing the speed bump was as good as 92 to 99%.

Summarizing, the road profile was not recreated, however we obtained an accurate road load data reconstruction. For this reason, it is reasonable to use vehicle durability test stands for testing the vehicle structure and the results are reliable and repeatable.

3.2. Collected data

The sensors installed on the vehicle collected data during real-time journeys. The measurement results were classified according to type of roads for loaded and unloaded vehicle, respectively. About 5 hours of data were collected for the unloaded semitrailer and about 7 hours for the loaded one. Exemplary records from selected sensors for unloaded semitrailer journeys are presented in Fig. 10.
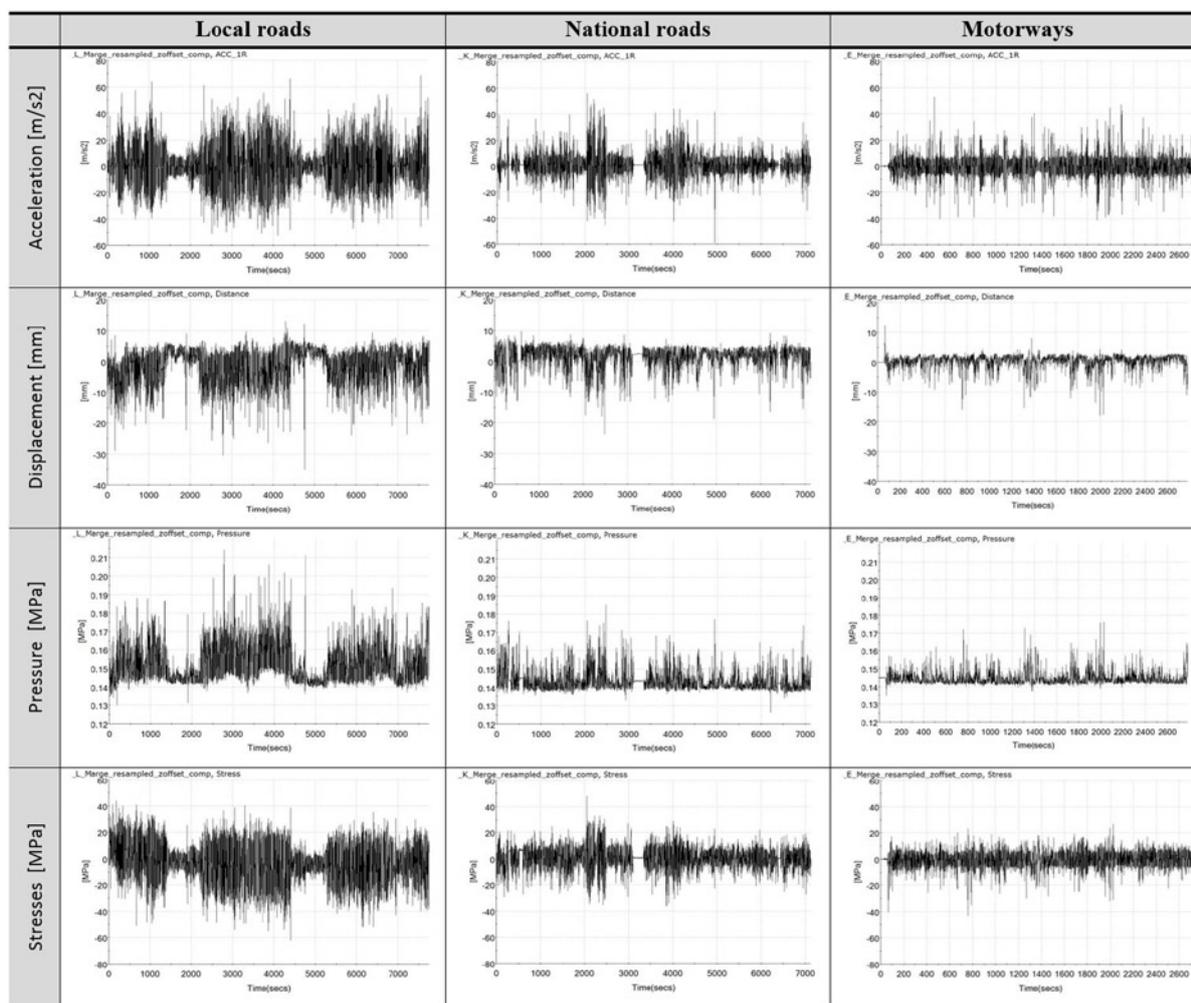
Fig. 10. Sample time series in selected measurement places for unloaded trailer
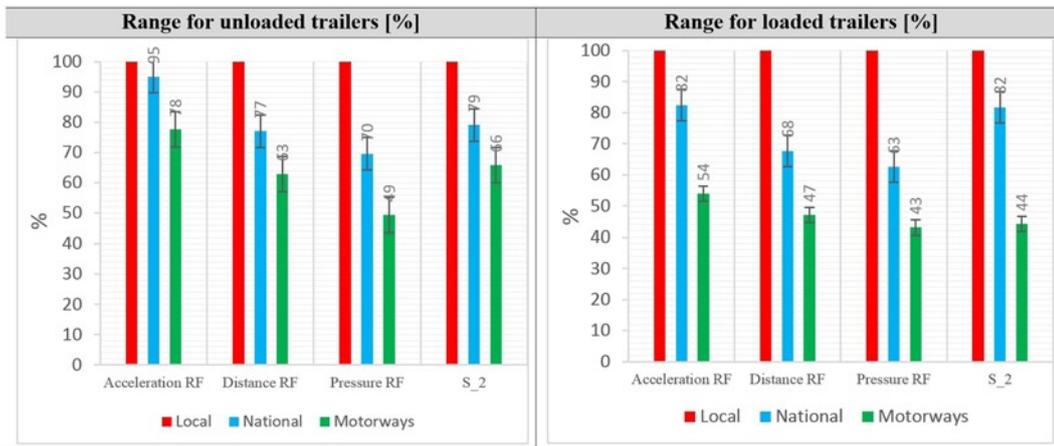
Fig. 11. Statistical range of acceleration, displacement and pressure changes on right front wheel and changes in stress in S2 for loaded and unloaded trailer
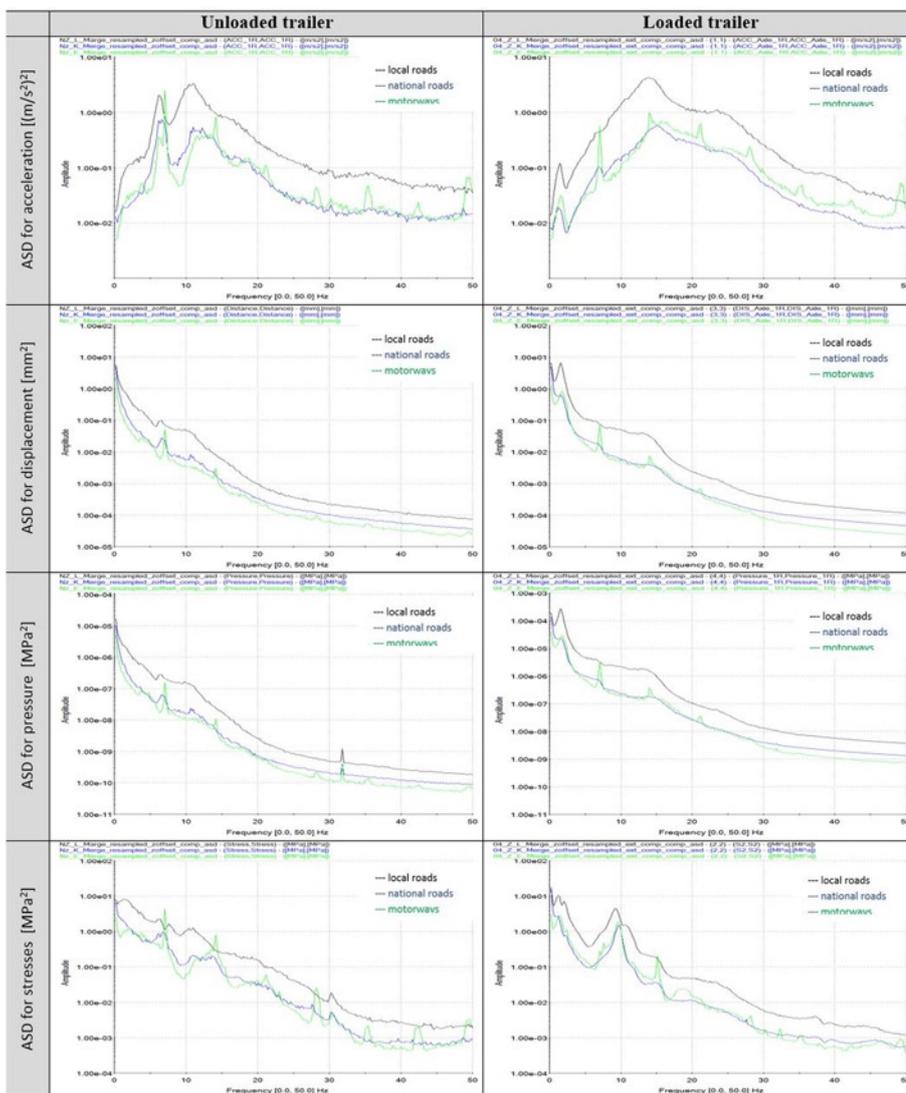
Fig. 12. ASD for acceleration, displacement and pressure on right front wheel and stresses in S2 for unloaded trailer

The graphs show time histories for the acceleration, displacement and pressure on the right front wheel and changes in stress registered by the strain gauge installed in the front of the frame. For different registered physical quantities the graphs illustrate the different nature of collected data variability depending on the type of the road on which the vehicle travelled.

In order to have a closer look at the parameters characterizing individual roads, the range of measured signal was compared for three types of roads. The values of measured signals were also compared for the unloaded and loaded vehicle to find out how the range of the recorded parameters changes in relation to vehicle load. Fig. 11 shows the range of acceleration, displacement and pressure changes registered on the front right (FR) wheel axle and changes in stress in the front part of the frame (S2) for local roads, national roads and motorways. It appears from the charts that the range of registered signals for the national roads is 20% to 30% smaller than for local roads, while that for motorways is 20%-50% lower than for local roads. The scope of change is different for the different analysed physical quantities.

When analysing the difference between tests with loaded and unloaded trailer, in the case of accelerometers for the unloaded trailer, the difference between the motorway and the local road is 22%, where in the case of the loaded trailer it is 46%. A similar situation was noted for signals from strain gauges. The distance and pressure sensors show similar range between loaded and unloaded vehicle data. These differences are confirmed in the analysis of the frequency of the recorded signals, presented in Fig. 12. Signals from accelerometers and strain gauges have higher frequencies, from 7 to 15 [Hz], while the displacement and pressure signals, have lower frequencies up to 5 [Hz].

In order to compare the character of motion an auto spectral density analysis was carried out for selected signals. The results of the analysis are shown in Fig. 12. It appears from the spectra that the character of the signals is similar and that local roads generate the highest amplitude. National roads and motorways show a similar character for a similar level of amplitude.

3.3. Generated drive data in time domain

On the basis of all the collected road load data the drive signal in time domain was generated for the investigated types of roads and the loaded and unloaded trailer. Fig. 13 shows (using as an example acceleration on the right front wheel) that the road data are very well reconstructed on the test rig. The reconstruction correlation of over 91% was achieved. Drive data signal was generated for the adopted model through iterations. The iterations were performed for the selected part of a local road. The RMS response on the installed sensors shows about 90% reconstruction for accelerometers and 85-97% reconstruction for distance sensors regarding the RMS of the input signals (Fig. 14).

Using the validated model, drive data signal in time domain was generated for each wheel, as a signal representing the displacement
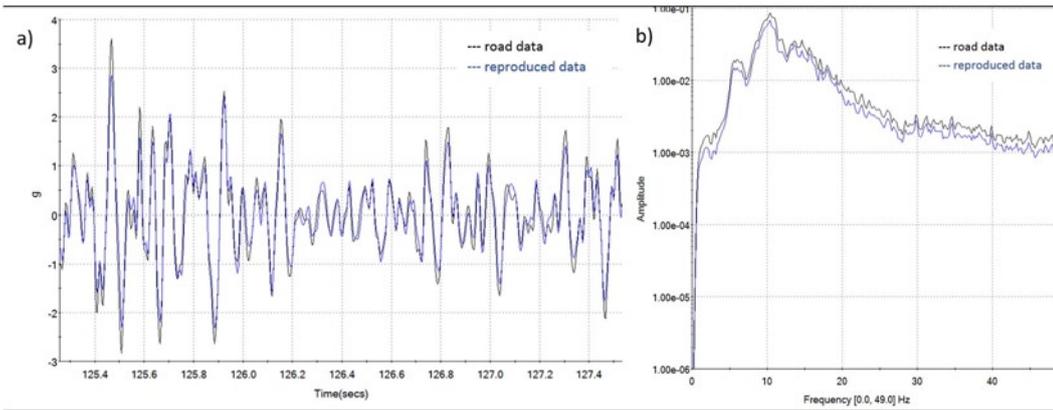
Fig. 13. Comparison of data collected from roads and data reconstructed on test rig for acceleration on first right wheel of unloaded trailer: a) time series. b) spectrum
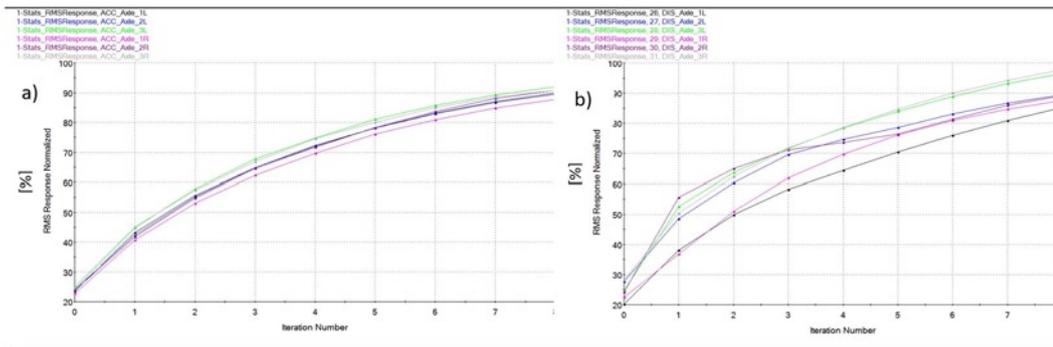
Fig. 13. Comparison of data collected from roads and data reconstructed on test rig for acceleration on first right wheel of unloaded trailer: a) time series. b) spectrum
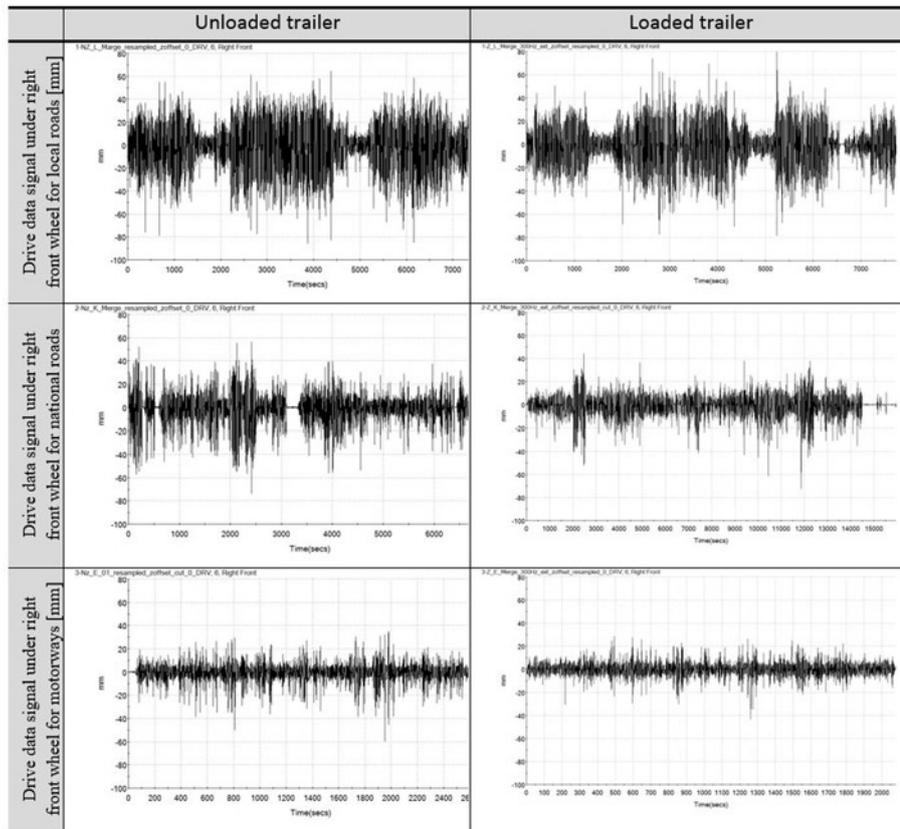
Fig. 14. RMS response of selected sensors during generating drive signal iterations: a) accelerometers on axles, b) distance sensors on axles

of the hydraulic actuator located under the wheel over time. Fig. 15 shows drive data signal obtained for the selected right front wheel. The signal graphs reflect road bumpiness under the wheel. In the investigation the stiffness of the tire was taken into account, whereas the rolling effect of the wheel was neglected [21]. The graphs were plotted and compared for the unloaded vehicle and the loaded one. The range of statistical changes for the selected profile under the front right wheel is shown in Fig. 16. It is apparent that for the unloaded trailer local roads generate 15% wider range of variability than national roads and 35% wider range in comparison with motorways. For loaded trailer local roads generate 25% and 55% wider range of variability than national roads and motorways, respectively.

In order to compare the character of the generated drive data under the wheels, an auto spectral density analysis was carried out for each of the signals. The ASDs for right front wheel for different roads are shown in Fig. 17. The ASDs for the different road conditions for both unloaded and loaded trailer have a similar character. The main frequency is around 1 [Hz]. It is interesting to note that the ASDs for national roads and motorways differ only at the dominant frequency of about 1 [Hz] while at higher frequencies they are at the same level. A comparison of the level of amplitude in the dominant frequency band for the loaded and unloaded trailer shows that the level for the unloaded trailer is higher than for the loaded one (Fig. 18).

The presented results (for the loaded and unloaded trailer) show over 90% correlation between the reality and the reconstruction, regarding the RMS of collected and reconstructed signals. In the case of two distance sensors the obtained correlation is as high as 97%.

Even though the identification process did not take into account the dynamic stiffness of the tire, resulting from the wheel rotation [21], it is worth to notice that we obtained very high level of reconstruction for the registered road load data. Moreover, a similar level of correlation (98%) was achieved by D. Chindamo [4] on a four-poster simulator. As reported by L. Telloa [23] the elaborated road data in time domain can be directly used in FEM calculations, giving the results comparable with those obtained using the real data.
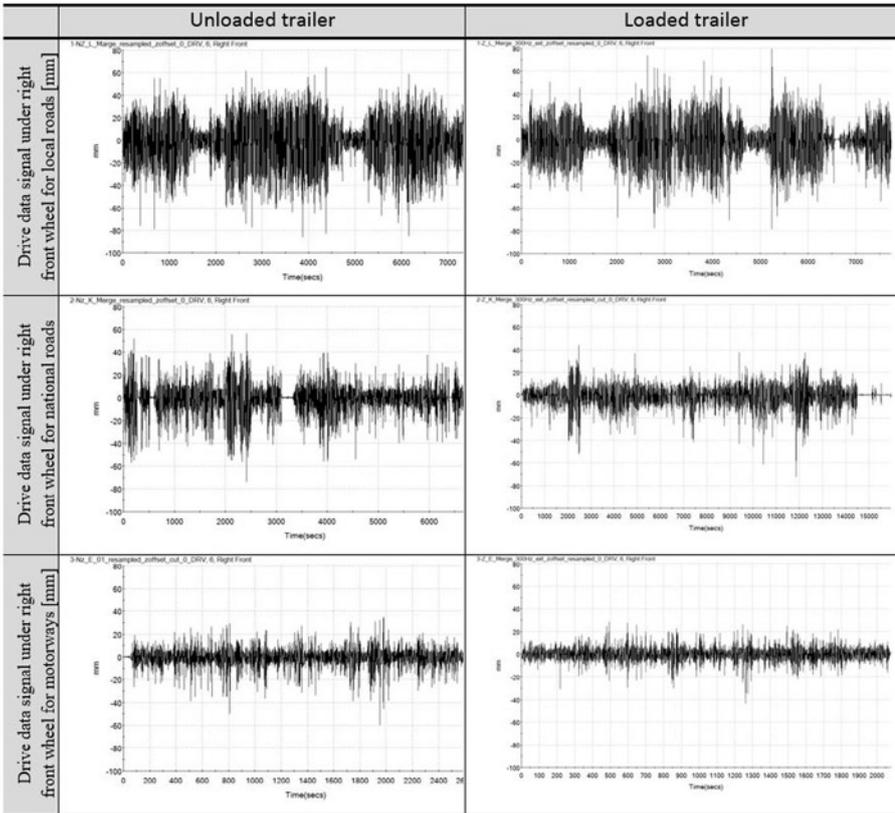
Fig. 15. Drive data signal as displacement of actuators in time domain for selected right front wheel
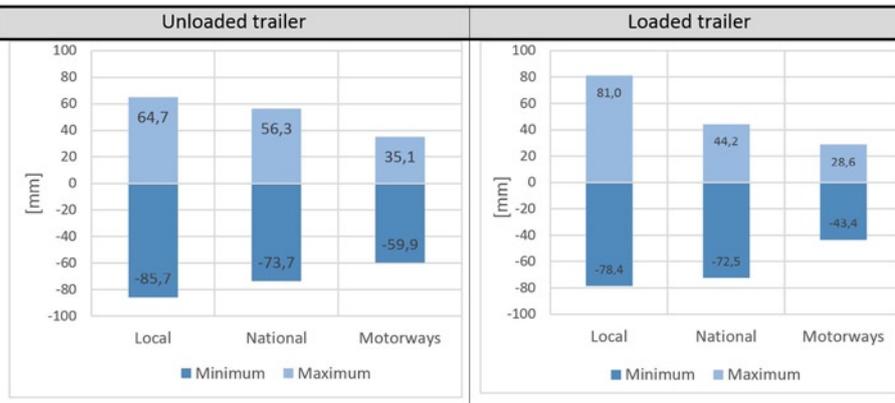
Fig. 16. Statistical range of displacement for drive data signal under right front wheel
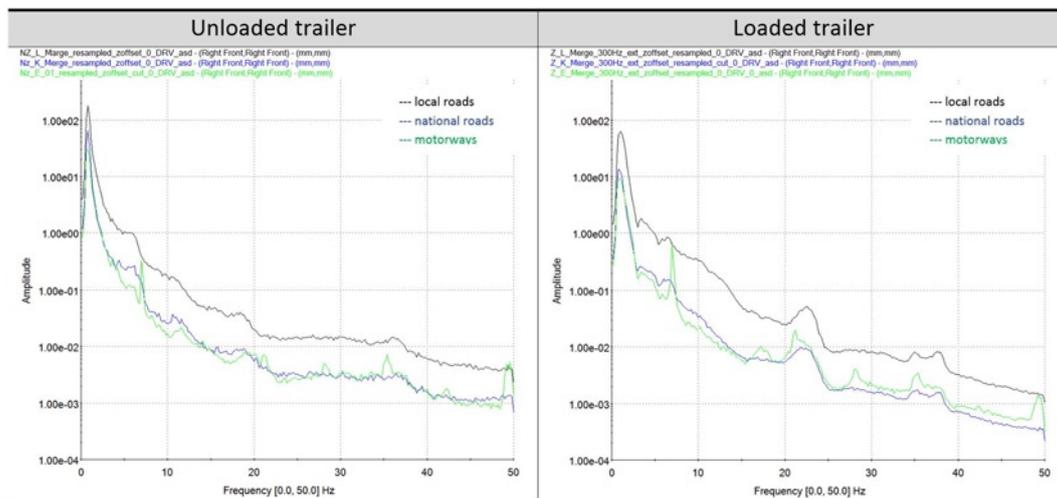
Fig. 17. Auto spectral density for estimated drive data under right front wheel for different roads

4. Conclusions

Based on the verification tests it was found, that the reconstruction of changes in physical quantities, recorded on the vehicle, such as displacement or acceleration while passing the speed bump, was from 93 to 99% (regarding RMS of measured and reconstructed signals). On the other hand, it should be stated that in the case of the maximum displacement of the actuator under the wheels of the vehicle, on the MTS 320 road simulator, while passing the speed bump, the difference between the real road profile and the obtained one was up to 11%. Also, the obtained profile width, resulting from the radii of the tire, is greater. Therefore, the displacement of the actuator under the wheel in the road simulator, cannot be considered as a road profile.

Presented methodology of reconstructing the dynamic loads under different road conditions, have shown an accuracy of 91% for comparison between the RMS value, measured by accelerometers during simulation, and the reference signals reached from the roads. In the case of displacement sensors the achieved accuracy values were in the range of 85-97% regarding the real signal.

The methodology is accurate for different types of roads and different conditions. The road data were collected at different driving speeds, in different weather conditions, on various roads and a large number of kilometres were travelled, whereby practically all possible road situations were covered.

The elaborated drive data signal under the wheel, in time domain, includes vehicle speed and the signals can be directly used in FEM or fatigue calculations. At the same time as the road data is being recorded, information about, what happens in the vehicle structure is recorded. This information can be correlated with the data on the conditions under the wheels. On this basis, one can determine the dependence between the drive data and the response of the vehicle structure.

By comparing different road conditions, the manufactured vehicle's lifetime can be estimated. At the design stage its necessary to have
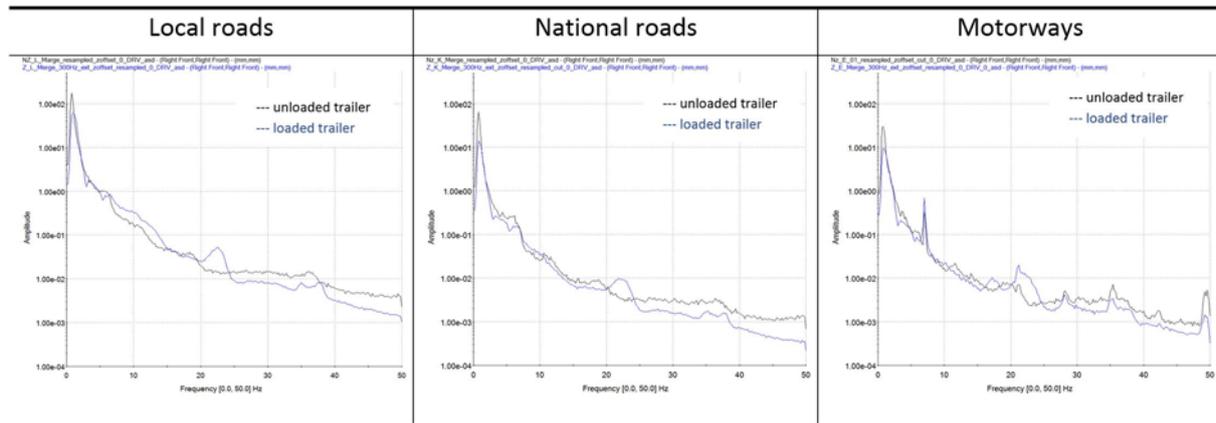
Fig. 18. Auto spectral density for drive data under right front wheel for loaded and unloaded trailer

knowledge about the roads on which the vehicle will be used and what kind of impact those different roads will have on the vehicle. The presented methodology can be used to estimate the impact of various road conditions on the heavy duty vehicle structure for loaded or unloaded configuration.

Further research on this subject will be devoted to the analysis of signals, including a fatigue analysis, aimed at determining the impact of different roads on the vehicle's life time.

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