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Impact of tram traffic on noise and vibrations

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The most important form of the public transport in town Zagreb is tramways, with 120 km of the tram tracks and 450,000 passengers transported every day. The noise and vibrations are today one of the major causes of reduced quality of life in the urban environments. That is confirmed by more and more frequent complaints from the citizens living and working in the urban areas along the traffic corridors with heavy road and tram traffic. This paper shows the survey on impact of tramway traffic on noise levels and vibrations. The tram vehicles from four manufacturers were considered: Duro Dakovic (Croatia), CKD Tatra (Czech Republic), Düwag (Germany) and Koncar (Croatia), which are used by the Zagreb Electric Tramways (ZET) company. The research also covered the new, low floor tram type TMK 2200, manufactured in Zagreb, and started being exploited in June 2005. The results of this research helped ZET to decide on the tram types first to be replaced with the new ones, and also provided specific guidelines for design and maintenance of the tram tracks, all that to undertake adequate measures to reduce noise and vibrations.

INTRODUCTION

The construction of tram tracks in highly valuable city areas should be approached cautiously, considering not only the economic and technical indicators but also ecological indicators, i.e. reduction of noise and vibration resulting from tram passage. The research presented in this paper was carried out on tram tracks in Zagreb due to the specificity of this city in comparison with others in Europe which use the tram as the backbone of the public transportation system. The specificity is in the great traffic volume (15 million gross tons/year per section) and in small tram service interval (less than 1 minute) [1]. Due to this specificity, a special system of the construction of the permanent way of the tram track has been developed, called the “Zagreb System”, fig. 1. For the purpose of reducing noise and vibration, the rail foot and web are covered with flexible elements. As seen in the figure, the tram track consists of two rails, type Ri-60, fixed to a continuous reinforced concrete base, 200 cm wide and 25 cm thick. The gauge of the tram track in Zagreb is 1000 mm, and it is usually closed with reinforced concrete prefabricated plates (as in fig. 1). Depending on the track position, there are still two types of enclosure used in Zagreb: filling with concrete and a final layer of asphalt (most common at intersections of road and tram track) and with crushed stone where the tram track is in a separate lane.

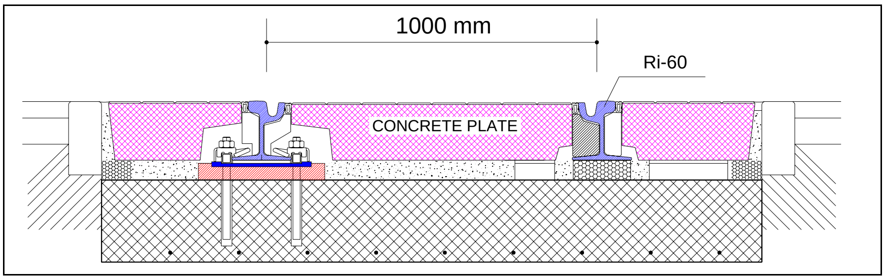

Figure 1. The "Zagreb System"

In consideration of noise and vibrations arising from the movement of vehicles on tracks (trains, trams), the focus is directed at studying the interaction of wheel and track. The reason for this is that the greatest influence on increasing noise and vibration results from irregular wheels (flat spots, unrounded wheels) and irregularities on the rail running surface (corrugations, rail joints, welds). Increases of noise and vibration which result from tram passage depend not only on the track (characteristic of rail running surface, type of track construction, manner of track enclosure) but also on the type of vehicle (type, age, speed, type and condition of tram vehicle wheels). In general, it can be said that the system of tram/track represents a complex problem in the field of vibrations [2].

The research presented in this paper was conducted in cooperation with the company Zagreb Electric Tramway (ZET) within the framework of the scientific project "Permanent way of urban railways", financed by the Ministry of Science and Technology of the Republic of Croatia. Due to the reasonable scope of the study, the research focused on observing the influence of the type of tram vehicle on noise levels and vibration intensity, with consideration of the following: manner of track enclosure, rail fastening system and geometry of rail running surface.

1. DESCRIPTION OF FIELD MEASUREMENTS

Measurement of noise levels and vibration resulting from tram passage were carried out at several locations in the City of Zagreb. Noise levels were measured on new tracks and tracks in use a certain number of years. This is due to the fact that new tracks do not have the rail running surface irregularities in comparison to those tracks in use for longer periods of time which, as a rule, show geometric irregularities on the rail running surface. Tram constructions were considered with respect to the system of fastening the rails to the base and with respect to the manner of track enclosure. Noise levels were measured on tracks enclosed with reinforced concrete plates and crushed stone (30/60 mm grading) and on tracks where the DEPP and ZG 3/2 fastening system was employed, fig. 2. The vibrations of tram track was measured on tracks with an even rail running surface, using the DEPP fastening system and enclosed with reinforced concrete plates.

In the measurement of noise levels and vibration, several types of tram vehicles by different manufacturers were studied: type T4 and type KT4 by the manufacturer CKD Tatra, type TMK 101 and type TMK 201 by manufacturer Duro Daković, type GT6 by manufacturer Düwag and type TMK 2100 and TMK 2200 by manufacturer Koncar. In measuring vibration intensities, tram types TMK 2100 and TMK 2200 were not studied.

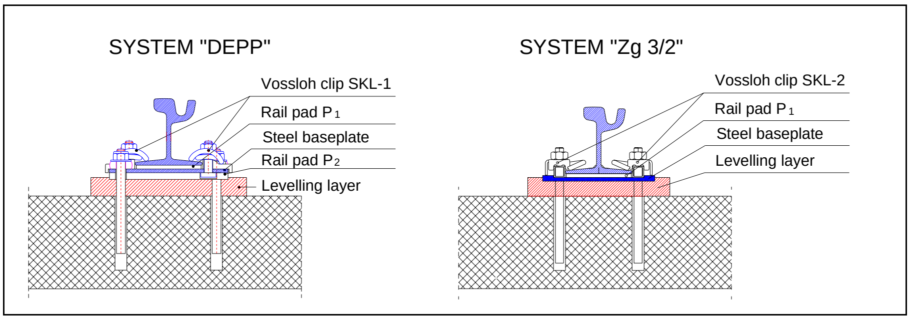

Figure 2. Fastening systems of tram tracks in Zagreb

1.1. Measuring noise level

Measurements of noise levels were conducted using measuring equipment by the manufacturer Brüel & Kjær, with analysis of measurement results conducted using the program EVALUATOR 7820 by the same manufacturer. This paper shows the comparative analysis of the type of tram on noise levels dependent on the consideration of the influence of individual elements of track construction: type of track enclosure, system of fastening the rail to the base and characteristics of the rail running surface [3, 4, 5]. During each measurement, noise levels for a minimum of five tram passages of each type of tram vehicle were measured at each location. Measurement of the time for passage between two fixed points allowed for determination of tram travelling speed. Noise levels were measured at a distance of 1 m from the tram track at a height of 1.2 m from running surface of the rail. A typical depiction of the measurement is shown in fig. 3.

Figure 3. Presentation of noise level measurement

Prior to measuring noise levels, the rail running surface was surveyed using the profilograph (device for measuring rail irregularities). As an illustration of irregularities, the figure below shows a photograph of the rail irregularities in the weld zone and a graphic depiction of the recorded geometry of the running surface at the same spot, fig. 4.

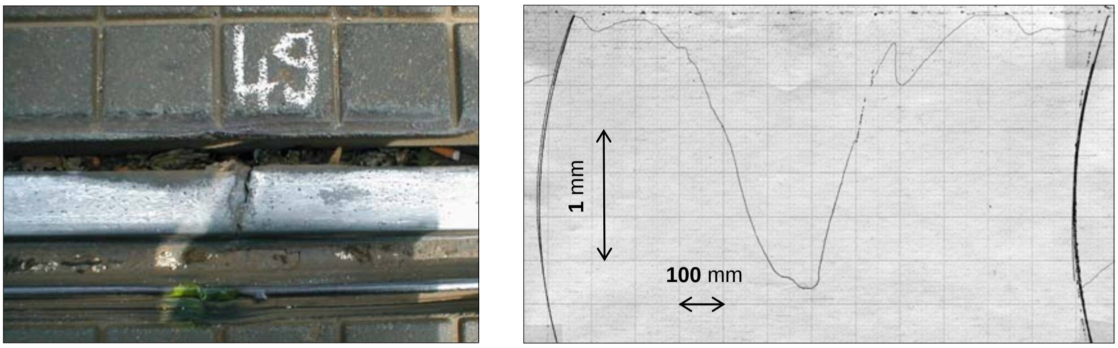

Figure 4. Photograph of the weld and vertical weld geometry

1.2. Measuring vibrations

Measurements were carried out during daylight hours on Republic Austria Street on a new track (45 days after its installation) [6]. Measurement of vibrations on the new track enabled the team to avoid all degradation of elements fastening the rail to the base which are characteristic for tracks in use for a certain number of years. This primarily refers to irregularities of the running rail surface and the degradation of elastic elements within the tram construction. Namely, irregularities of the rail running surface (corrugation, rail joints and geometric weld irregularities) and degradation of elastic elements greatly influence an increase in vibrations. With the elimination of such influences of the degradation of the track construction, it is made possible to better compare the influence of individual types of tram on vibration. Vehicles with wheel irregularities, such as flat spots, were not considered as they caused an increase in vibration from 5 to 10 dB with respect to 10^{-4} m/s^2 in comparison to new wheels [2]. Three accelerometers were used in the measurements, each set up on a steel device weighing 35 kg placed on the asphalt surface next to the tram track at a distance of 2.0 m from the track axis, fig. 5.

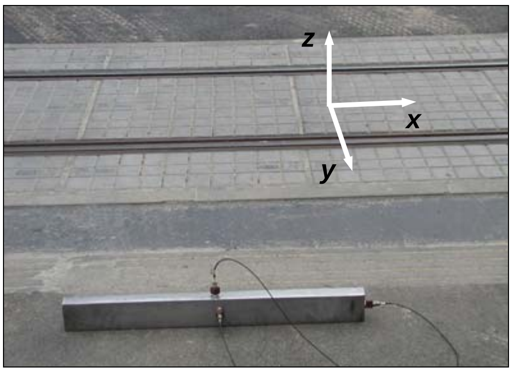

Figure 5.

Presentation of vibrations measurement

Vibrations were measured at the moment of tram passage for a time period of 8 seconds in three mutually perpendicular directions: vertical direction (z) and two horizontal directions (x and y). The x axis was the direction of tram movement, i.e. the direction of the tram track, while the y axis was perpendicular to the track axis, though in the same plane, fig. 5. Vibration measurement on the track was conducted by the Koncar – Vibroacustic laboratory [7].

2. MEASUREMENT RESULTS

At each measurement location, noise level and vibration were measured for the passage of five vehicles of each type of tram vehicle studied. Noise levels were measured for the passage of all types of tram vehicles included in the ZET rolling stock. However, in the measurement of vibrations, the low floor TMK 2200 tram was not studied as this vehicle was only recently introduced to the ZET rolling stock.

2.1. Noise levels

In the assessment of the influence of the type of trams on noise levels in urban areas, maximum noise levels (L_{max}) were used as the equivalent levels were dependent upon total noise levels in the measurement period. The maximum levels (peaks in the measurement diagrams) appeared following the passage of tram vehicles along the track and in part due to the passage of motorcycles and heavy cargo vehicles along the road. A characteristic presentation of time dependent changes of noise level obtained in measurements at one location is shown in fig. 6.

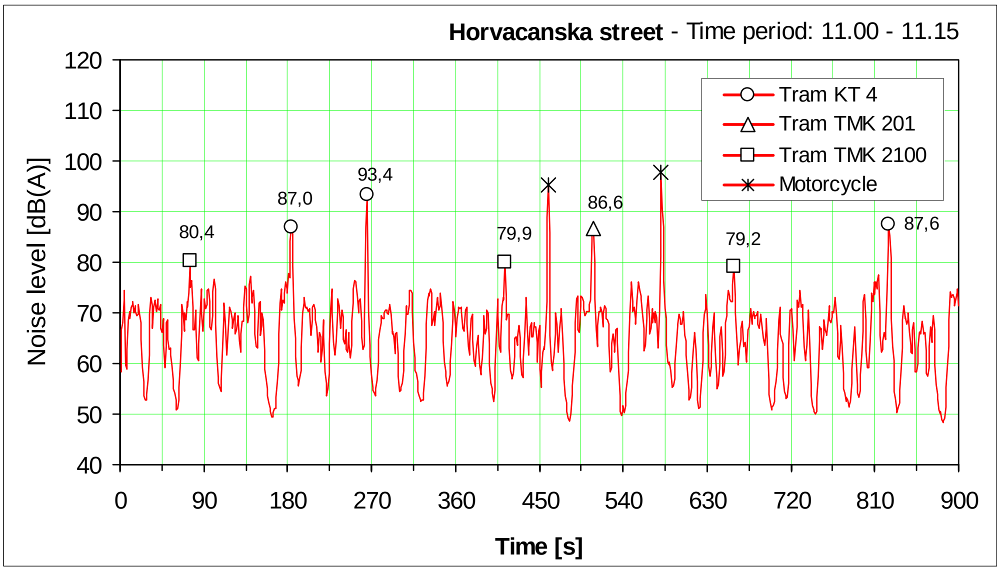

Figure 6. Representation of time dependant changes of noise level

2.1.1. Noise levels depending on tram type and method of track enclosure

The passage of seven types of tram vehicles on tracks enclosed with reinforced concrete slabs and crushed stone were considered. These two variations of track enclosure were selected as the majority of tram tracks in the City of Zagreb are enclosed with the said materials. The mean values of maximum noise level dependent on vehicle type and method of track enclosure are shown in fig. 7. As the figure shows, the mean value of the maximum noise level measured on tracks enclosed with reinforced concrete slabs is 0.5 to 2 dB(A) less than noise levels for trams travelling along tracks enclosed with crushed stone. The diagram clearly shows that the passage of tram types T4, KT4, TMK 101 and TMK 201 cause a significant increase in noise levels, from 5 to 7 dB(A) in comparison to the passage of tram types GT6, TMK 2100 and TMK 2200.

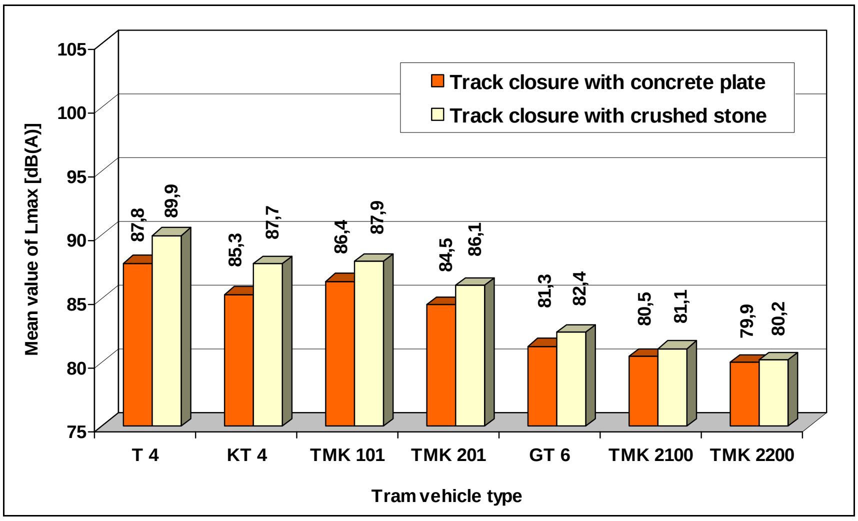

Figure 7. Mean values of L_{max} depending on vehicle type and track enclosure method

2.1.2. Noise levels depending on tram type and rail fastening system

The research was carried out on two types of rail fastening systems: the DEPP system (double elastic fastening system) and the ZG 3/2 system (single elastic fastening system). The above stated systems are used for tram tracks in Zagreb for concrete foundations. The DEPP system falls into the group of indirect elastic fasteners while the ZG 3/2 system falls within the group of direct elastic fasteners. The measurement of noise levels in this analysis were conducted on tracks with smooth running surfaces. The mean values of maximum noise levels dependent on the type of vehicle and rail fastening system were compared, and the results are shown in fig. 8.

This figure shows that noise levels are 0.2 to 2 dB(A) less on tracks fastened using the DEPP fastening system for the passage of specific tram types. Tram types GT6, TMK 2100 and TMK 2200 again showed the best results in this comparison. It is evident that the difference between the "noisiest" tram (type T4) and the "quietest" tram (type TMK 2200) is 6.2 dB for the ZG 3/2 fastening system and the 7.2 dB(A) for the DEPP fastening system.

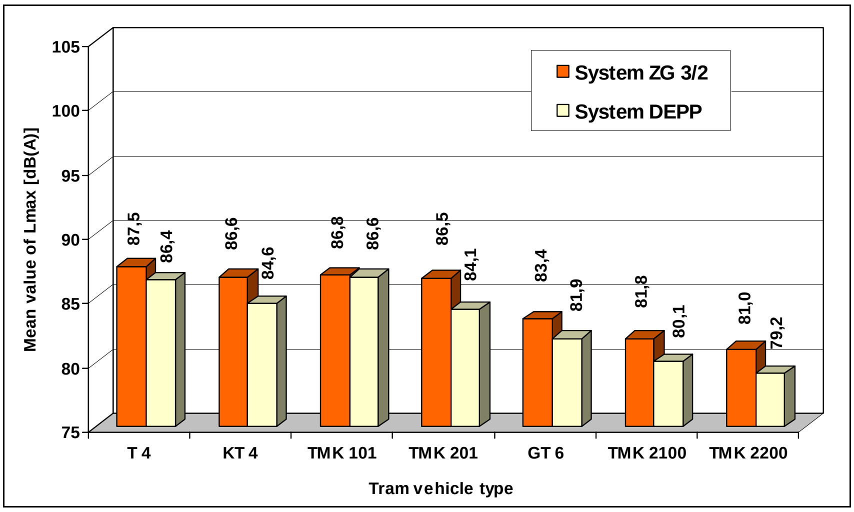

Figure 8. Mean values of L_{max} depending on vehicle type and the rail fastening system

2.1.3. Noise levels depending on tram type and rail running surface geometry

Geometric irregularities on the rail running surface cause not only an increase in load on the track but also reduce the effect of track fastening, thereby worsening track geometry, negatively influencing the vehicle, reducing passenger comfort and increasing noise levels. In order to establish the influence of irregularities on the rail running surface on the increase of noise levels, measurements were first taken on tracks with smooth running surfaces and then on tracks with irregularities on the running surface. Vertical irregularities of the running surface ranged from 1.0 to 2.3 mm. The greater depth of irregularities is caused by the strong impact of the vehicle wheel at the moment the vehicle passes over the irregularity and results in a significant increase in noise levels. The mean values of maximum noise levels dependent on tram type and the geometry of the rail running surface are shown in fig. 9.

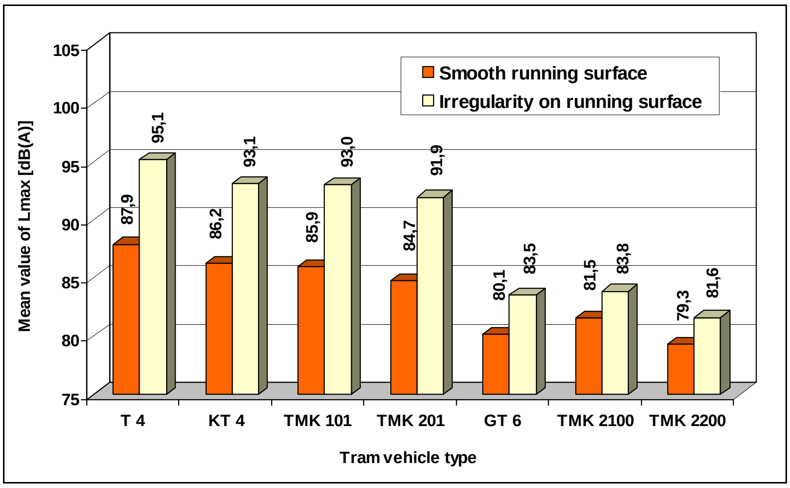

Figure 9. Mean values of L_{max} depending on vehicle type and geometry of running surface

A comparison of the mean values of maximum noise levels of tram passage over irregularities in the running surface showed that passage of tram types T4, KT4, TMK 101 and TMK 201 caused the largest increase in noise levels, up to 7 dB(A). Again, tram types GT6, TMK 2100 and TMK 2200 showed the best results in this analysis.

2.2. Vibration

As the Republic of Croatia does not have any valid recommendations, regulation or standard in the field of vibrations the research was conducted according to the German standard DIN 4150 [8, 9]. According to these standards, vibrations impact on people, i.e. equal perception of vibration by human beings is defined by means of the non-dimensional coefficient KB, and limit values are shown in table 1.

Table 1. Classification of vibration levels

KB ≤ 0.1	not noticeable vibrations
0.1 < KB ≤ 0.4	hardly noticeable vibrations
0.4 < KB ≤ 1.6	noticeable vibrations
1.6 < KB ≤ 6.3	strong vibrations
KB > 6.3	very strong vibrations

During the research, the effective values of speed v_{RMS} [mm/s] were assessed in the frequency range of 1 to 80 Hz. To assess the vibration, the frequency spectra of vibration at the moment of maximum measured vibration for each tram passage were determined. The results are depicted in the form of a time diagram of vibration with duration of 8 seconds and the third-octave frequency spectrum with set boundaries of vibration, fig. 10.

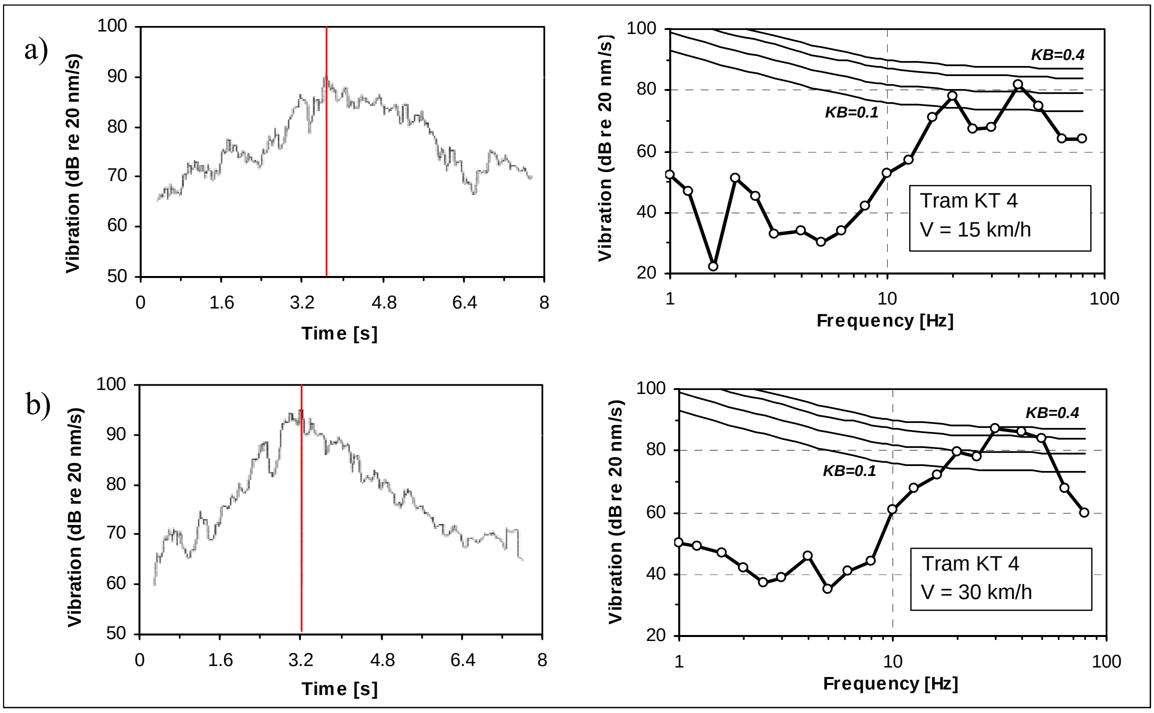

Figure 10. Tram KT4: a) V = 15 km/h, b) V = 30 km/h

The measurements established that the speed of the vehicle driving at the observed location ranged from 15 to 40 km/h changes in vibration at such relatively low speeds did not have a significant influence. Figure 10 shows that the magnitude of the vibrations at speeds of 15 km/h and 30 km/h are approximately within the same boundaries for the same type of vehicle. The measurement results showed that vibrations in directions *x* and *y* were not noticeable, i.e. KB ≤ 0.1. As such, only vibrations in the *z* axis were measured for each type of tram, fig. 11.

The figures show only a few of the results obtained in the measurement and analysis of vibration data in the *z* axis. The most favorable results were obtained for tram type GT6. It is evident that the vibrations in the *z* direction are unnoticeable, fig. 11. For tram types TMK 101 and TMK 201, the vibrations were hardly noticeable, with KB ≤ 0.2. The poorest result was obtained for the KT4 type tram, for its results were on the boundary between hardly noticeable and noticeable vibrations. One interesting result was that the older type GT6 vehicle obtained better results than the KT4 and T4 tram types. Track vibration during passage of tram types TMK 2100 and TMK 2200 were not measured, as the TMK 2100 does not pass through the measurement location and tram type TMK 2200 was only recently introduced to the ZET rolling stock.

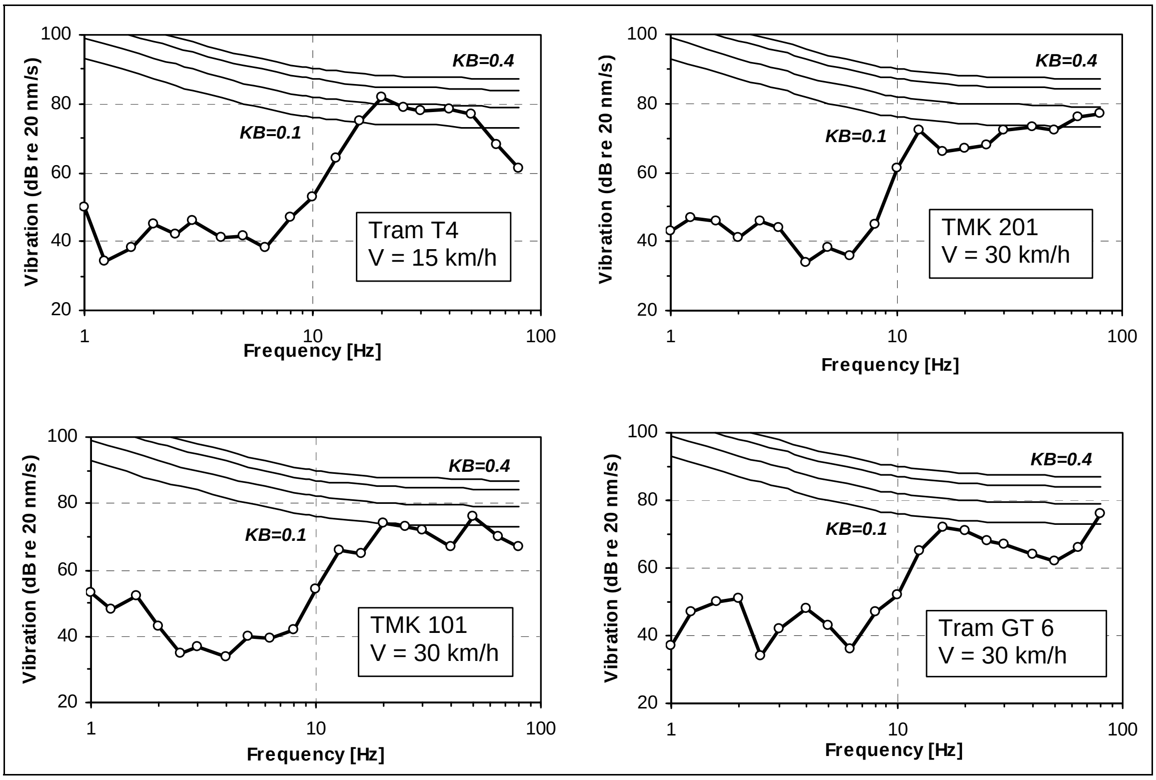

Figure 11. Vibration of individual types of trams in the *z* direction

CONCLUSIONS

Measurements of noise levels and vibrations, carried out within the framework of the broader project and described in part in this paper, served for the comparison of noise levels and vibration in the passage of various types of tram types on the track. The analysis was made by varying different track parameters: method of enclosure, track fastening system and running surface geometry. The research showed that of these three parameters, geometric irregularities in the rail running surface had the greatest impact on increasing noise during tram passage. In the analysis of weld geometry on noise levels, it was found that in irregularities where the vertical deviation is greater than 0.33 mm (this listed vertical deviation was analyzed at a length of 100 mm, meaning that the maximum slope angle is

3.3 mrad), the noise level increased from 1.5 to 10 dB(A) in comparison to the smooth running surface. In order to reduce increased noise levels during tram passby on tracks with rail running surface irregularities, it has been proposed to ZET (Zagreb Electric Tramway Company) that the permitted deviations of the rail running surface geometry have a maximum slope angle of 3.3 mrad [10, 11]. On tracks with smooth rail running surfaces, not only are noise and vibration reduced during passage of tram vehicles, but there is also reduced load on the rails (reduced dynamic impacts), which thereby reduces the costs of track maintenance.

The best results with respect to noise were obtained for the following tram types: GT6, TMK 2100 and TMK 2200. This can be explained by the fact that these vehicles have wheels with elastic elements and have a different concept for the relations between the bogie and the tram body. The poorest results with respect to noise levels and vibrations were obtained for these tram types: T4, KT 4, TMK 101 and TMK 201. As these vehicles are obsolete, a recommendation has been made to ZET (Zagreb Electric Tramway Company) that it is no longer advisable to invest in their general repair.

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