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Vibro-acoustic performance of newly designed tram track structures

Ivo Haladin[1], Stjepan Lakušić[1] and Maja Ahac[1]

[1]University of Zagreb Faculty of Civil Engineering, Zagreb, Croatia

E-mail: ihaladin@grad.hr

Abstract. Rail vehicles in interaction with a railway structure induce vibrations that are propagating to surrounding structures and cause noise disturbance in the surrounding areas. Since tram tracks in urban areas often share the running surface with road vehicles one of top priorities is to achieve low maintenance and long lasting structure. Research conducted in scope of this paper gives an overview of newly designed tram track structures designated for use on Zagreb tram network and their performance in terms of noise and vibration mitigation. Research has been conducted on a 150 m long test section consisted of three tram track types: standard tram track structure commonly used on tram lines in Zagreb, optimized tram structure for better noise and vibration mitigation and a slab track with double sleepers embedded in a concrete slab, which presents an entirely new approach of tram track construction in Zagreb. Track has been instrumented with acceleration sensors, strain gauges and revision shafts for inspection. Relative deformations give an insight into track structure dynamic load distribution through the exploitation period. Further the paper describes vibro-acoustic measurements conducted at the test site. To evaluate the track performance from the vibro-acoustical standpoint, detailed analysis of track decay rate has been analysed. Opposed to measurement technique using impact hammer for track decay rate measurements, newly developed measuring technique using vehicle pass by vibrations as a source of excitation has been proposed and analysed. Paper gives overview of the method, it's benefits compared to standard method of track decay rate measurements and method evaluation based on noise measurements of the vehicle pass by.

1. Introduction

Urban railway design is often influenced by the vibro-acoustic performance parameters. This is due to the fact that the railway track resides very close to surrounding structures (residential or business buildings, infrastructure etc.) where people live and work in. In Europe such areas are regulated by standards controlling noise and vibration levels [1], [2] that people are exposed to in their living or working environment. For that reason, light rail, metro and tram tracks have to incorporate certain level of vibration and noise damping components in order to achieve safe, comfortable, steady and quiet operation of railway vehicles.

It is very well known that the dominant source of noise emitted by rail vehicles at speeds greater than 40 km/h and lower than 250 km/h is in fact induced by interaction of wheel and rail at their interface due to unevenness or roughness of both surface of wheel and rail [3]. On the track side, the dominant radiator of noise is the rail that vibrates at high frequencies. It is possible to deal with wheel-rail interaction vibrations by controlling the smoothness of running surface of wheels and rails. Rail grinding can be a challenging and demanding task in collision with retaining level of service on busy urban rail systems running 24/7. Track can however by applying certain damping properties in design phase, absorb a portion of vibrations that would otherwise generate noise in the environment. Such damping properties can reduce noise at its source and reduce or eliminate the need of installing additional noise barriers or other means of noise mitigation measures.

Zagreb Municipality Transit System (ZET) acquired 140 new trams in recent years, thus changing the conditions on the tram network in terms of power demand, loads transferred to the track, wheel-rail interaction mechanism etc. Shortly after the introduction of new low-floor trams, it was observed that this fleet modernization has increased exploitation demands on other components of tram infrastructure [4]. In such conditions the deterioration of tram infrastructure

2. Design of new fastening systems for Zagreb Municipality Transit System (ZET)

The primary role of the rail fastening system is positioning and fixing of the rails and transferring the vehicle load from the rails to the track substructure. Generally, the type and characteristics of fastening system is chosen depending on the required elasticity of the track, planned load and type of rail. On major part of Zagreb tram tracks, grooved rails are discreetly laid on the levelling layer, made of micro synthetic concrete, built on reinforced concrete slab.

Standard fastening system used on a large part of ZET tram network is indirect elastic fastening system with decreased stiffness PPE with 50 MN/m stiffness, developed during the 1990s which do not meet today's highly complex exploitation requirements on Zagreb’s tram tracks such as high wheel loads on low-floor trams (more than 3.5 tons per wheel) and stricter environmental noise regulations (adoption of EU regulations [1]). Based these requirements, during the last few years the Faculty of Civil Engineering University of Zagreb has developed five different concepts for new fastening systems. Two of them, with working titles 21-CTT (based on Classic Tram Track) and 21-STT (Slab Tram Track), were chosen for further development. Their characteristics, production requirements and installation methods best match previous experiences in the construction and maintenance of tram tracks in Zagreb.

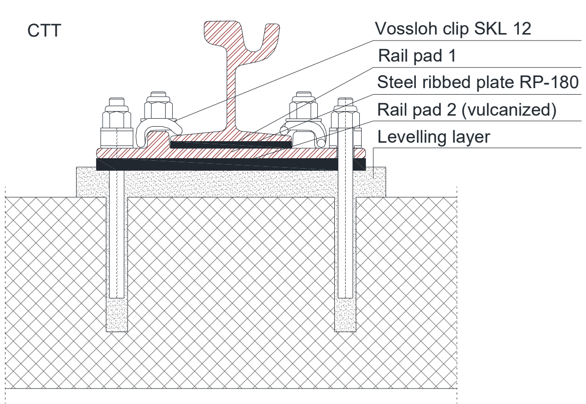

Figure 1. Cross section of 21-CTT fastening system.

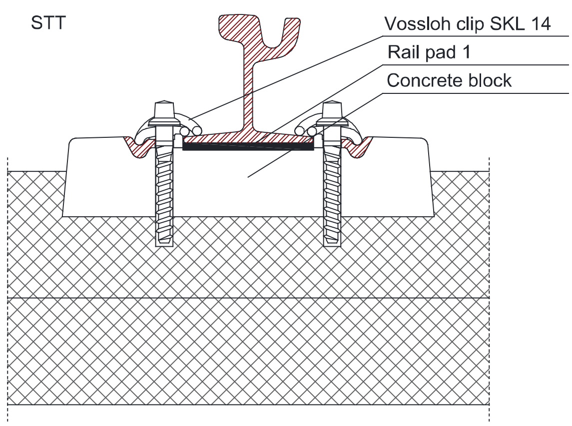

Figure 2. Cross section of 21-STT fastening system .

21-CTT system (Figure 1) places the rails discreetly on the levelling layer, made of micro synthetic concrete, built on reinforced concrete slab. The distance between supports is one meter in the tram rolling direction. The rail foot is supported by neoprene pads placed on ribbed steel plate, laid on the levelling layer. To ensure the durability of individual components and ease the installation during construction and dismantling during the track reconstruction, the underside of the ribbed steel plate is fitted, by vulcanization process, with elastic pad. Vulcanization process enabled production of a compact element electrically isolated from other components (anchors), but also provided for additional elasticity of the whole fastening system.

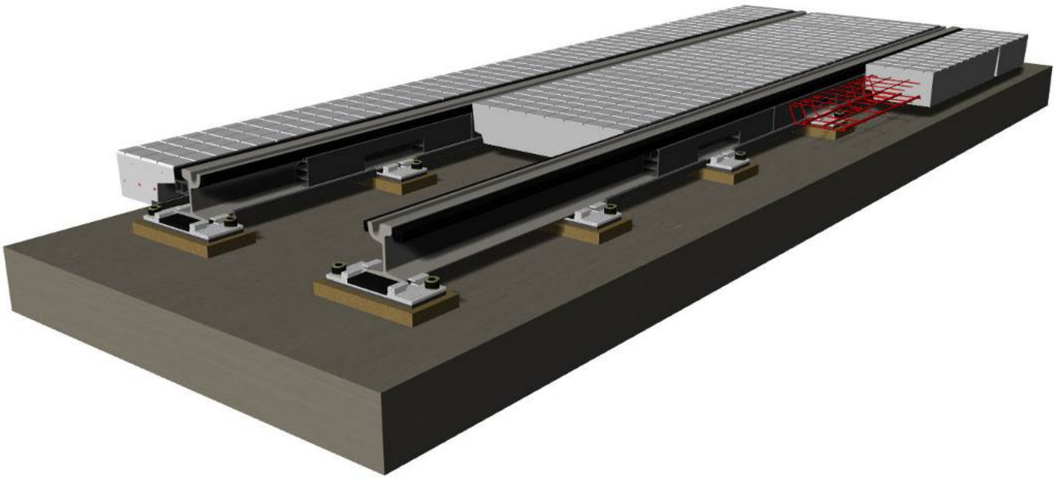

Figure 3. Design model of tram track structure with 21-CTT fastening system.

21-STT system (Figure 2) represents a completely new solution for tram tracks superstructure construction in Croatia. Its main advantage over the previous systems is that the levelling layer (which is quite difficult to construct) are replaced by two block precast concrete sleepers laid on reinforced concrete base slab, one meter apart (Figure 4). Upper reinforced concrete slab is constructed after track horizontal and vertical alignment adjustment. This is a direct elastic fastening system, with one elastic pad between the rail foot and block sleeper.

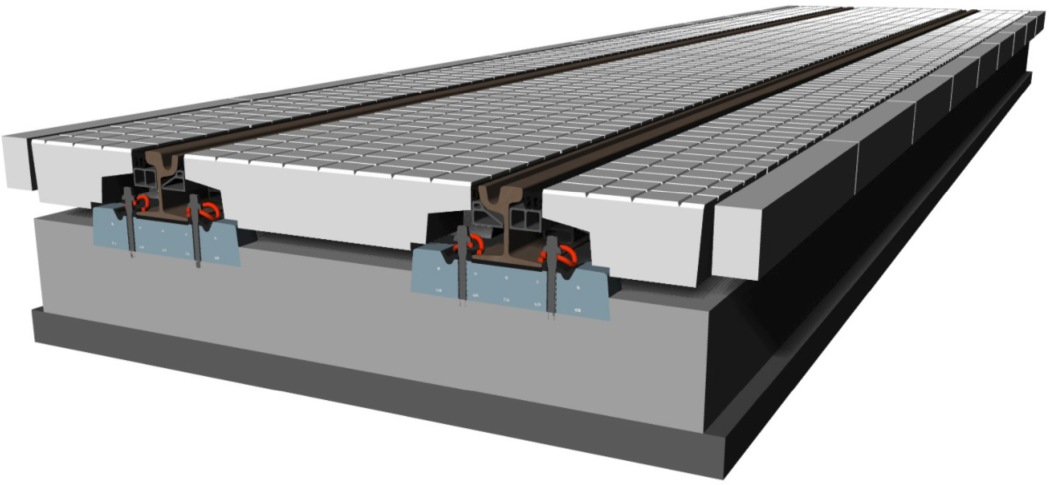

Figure 4. Design model of tram track structure with 21-STT fastening system.

3. Data acquisition at test site

To evaluate the newly designed track structures, test track has been installed in Savska street in Zagreb, providing the opportunity to observe and measure vibro-acoustic behaviour of 21-CTT, 21-STT track systems compared to PPE, a standard track fastening system commonly used on ZET network. Sub-sections of 21-CTT, 21-STT and PPE (each 50 m long) have been installed on 150 m long test track.

The test track incorporates different features for track monitoring:

- strain gauges in bottom zone of RC slab for strain and deformation monitoring,
- auxiliary shafts for easy access to equipment wiring and PC connections,
- small shafts next to the rails for access to the rail web and foot for accelerometer mounting,
- larger revision shafts for visual inspection of fastening systems along the test section.

Each test sub-section has been fitted with 4 strain gauges (two in horizontal, two in lateral direction in respect to a plain through rail running surface, Figure5), 4 accelerometers attached to rail foot and rail web for vibration measurements, Figure 6, and microphones along the track, 2.5 m away from the track axis.

Figure 5. Position of strain gauges prior to concrete casting on 21-STT subsection.

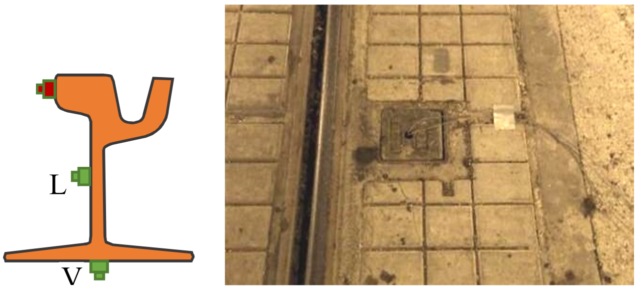

Figure 6. Position of accelerometers on a rail foot (vertical direction) and rail web (horizontal direction), inside a small shaft.

4. Measuring procedure and data analysis

At each sub-section, measurements of strain, noise and vibrations have been conducted using tram TMK 2266 as a source of excitation. The tram has been set to run at a constant speed of 15 km/h and 30 km/h along the three subsections. By using the same tram, under the same running conditions, differences in recorded levels of strain, vibrations and noise should are mostly influenced by track type the tram is running on.

4.1. Strain measurements

Strain reading on the bottom of concrete slab is a good indicator of load distribution through the track structure, influence of dynamic load on the lifespan of structure and possible cracks in the track structure. Data has been collected with sampling frequency of 50 Hz, giving a strain reading every 0.02 sec. Measurement results are shown in Table 1, where the overview of maximum strain readings of track structures is presented (for PPE, 21-CTT and 21-STT) for tram speed of 30 km/h.

By comparing the continuous time record of strain at all subsections (Figure 7) it is evident that 21-STT structure has very good load distribution to lower structure layers. Strain in this structure is around 3 times smaller than the other two observed subsections. It is also visible that structures 21-

CTT and PPE have similar strain measurements, as it was to be expected since similar fastening elements have been used in terms of load distribution.

Table 1. Values of strain reading at the bottom of RC slab.

Maximum strain reading [MPa]						
Section	PPE		21-CTT		21-STT	
Direction	LONG	LAT	LONG	LAT	LONG	LAT
24.11.2014.	**2.38**	**1.87**	**2.89**	**3.33***	**0.56**	**0.73**
04.03.2015.	**3.33**	**2.25**	**2.26**	**1.14**	**0.86**	**1.01**

*sensor is located near a rail weld of poor geometry so additional strain is to be expected

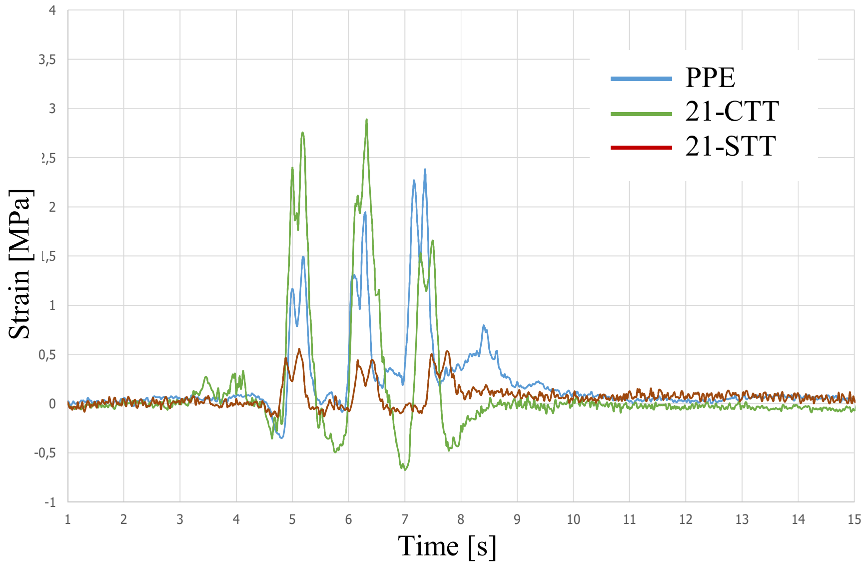

Figure 7. Time recording of strain measurements on three subsections.

4.2. Vibrations and track decay rate

Time recording of accelerations of rail in horizontal and vertical direction, under vehicle pass by has been recorded and used as a base for further analysis. Time recording of horizontal and vertical rail vibrations under TMK 2266 tram pass by have been analyzed. To express vibro-acoustic behaviour of a railway track, a parameter of track decay rate has been used. The contribution of noise emitted by rail vibration is a significant component of rolling noise up to 5 kHz [5]. One major factor affecting track noise performance has been identified to be the attenuation rate of vibration on the rail as a function of the distance from the excitation point [6], referred to as track decay rate measured in dB/m. Namely, the longer the section of the rail that vibrates, more noise is emitted to the environment. If the rail vibrations attenuate rapidly along the rail, and high decay rate is achieved, less noise is emitted.

Track decay rate is standardly measured by hammer impact method described in EN 15461:2011 [7] and very effective measurement technique on standard ballasted railway tracks [8]. On tramway tracks with higher decay rate values and different exploitation conditions (running surface shared with road vehicles, less time for conducting measurements), a method of measuring track decay rate from vehicle pass by time recording of vibrations is proposed [9]. Such a method has been adopted, modified and evaluated on the test section in Savska street.

Signal is first transferred to frequency domain and analyzed in 1/3 octave bands with center frequencies from 100 Hz to 5000 Hz. Track decay rate is based on the ratio of recorded rail vibrations around the wheels of the pass-by vehicle (T_{L1}) and vibrations of whole vehicle pass by (T_{L2}), Figure 8.

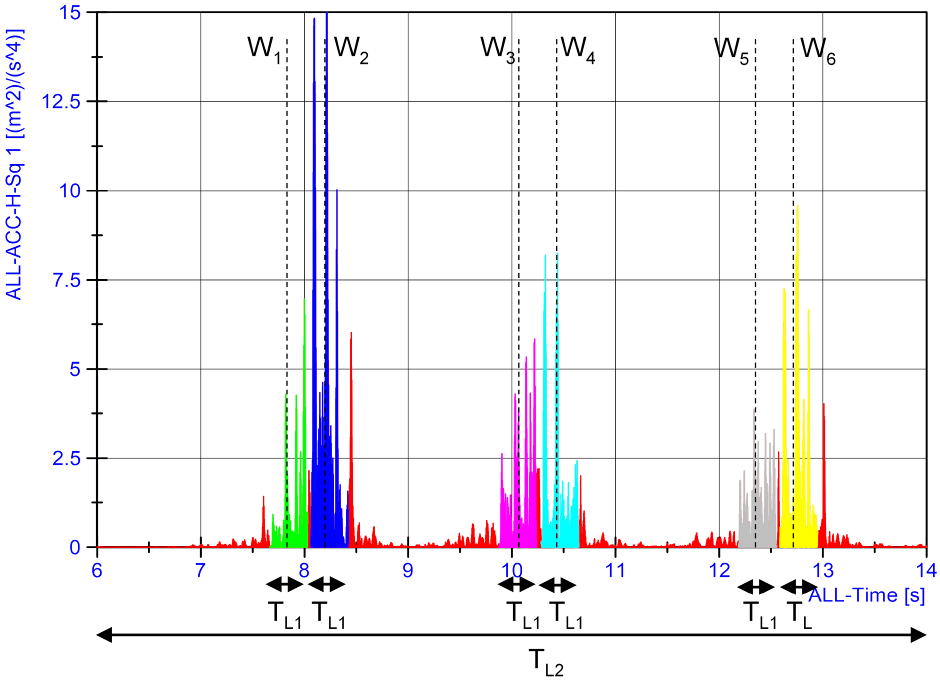

Figure 8. Time recording of vibrations with integration time T_{L1} around each wheel and T_{L2} for the whole tram pass by.

Calculated ratio, $R(f_c)$, of amplitudes around each wheel (A^2_{L1}) over amplitudes for whole tram pass by (A^2_{L2}) described in (1) is used to express track decay rate, TDR (f_c) for certain frequency band (2). Calculated track decay rate is further analyzed through energy iteration method to eliminate the influence of neighboring wheels on calculated decay rates of the observed wheel.

$$R(f_c) = \frac{A^2_{\sum L_1}(f_c)}{A^2_{\sum L_2}(f_c)} \approx 1 - e^{-\beta L_1} \tag{1}$$

$$\mathrm{TDR}(f_c) = -\frac{8.686}{L_1}\ln(1 - R(f_c)) \tag{2}$$

Detailed procedure of measurements is described in [10] while further relation to measured noise levels is analyzed through this paper. Using this method, decay rates on all three test sub-sections have been determined in vertical and lateral direction. Displayed results are averaged values of track decay rate (TDR) of 3 tram pass-bys.

It can be observed from Figure 9 that the vertical track decay rates are very similar on all three test sections in lower frequency range. In frequency range from 1000 Hz to 5000 Hz better performance of vibration attenuation is achieved by 21 CTT fastening system. 21 STT fastening system has the lowest TDR values i.e. less vibration attenuation due to its construction with only one elastic under-rail pad and overall stiffer slab track structure.

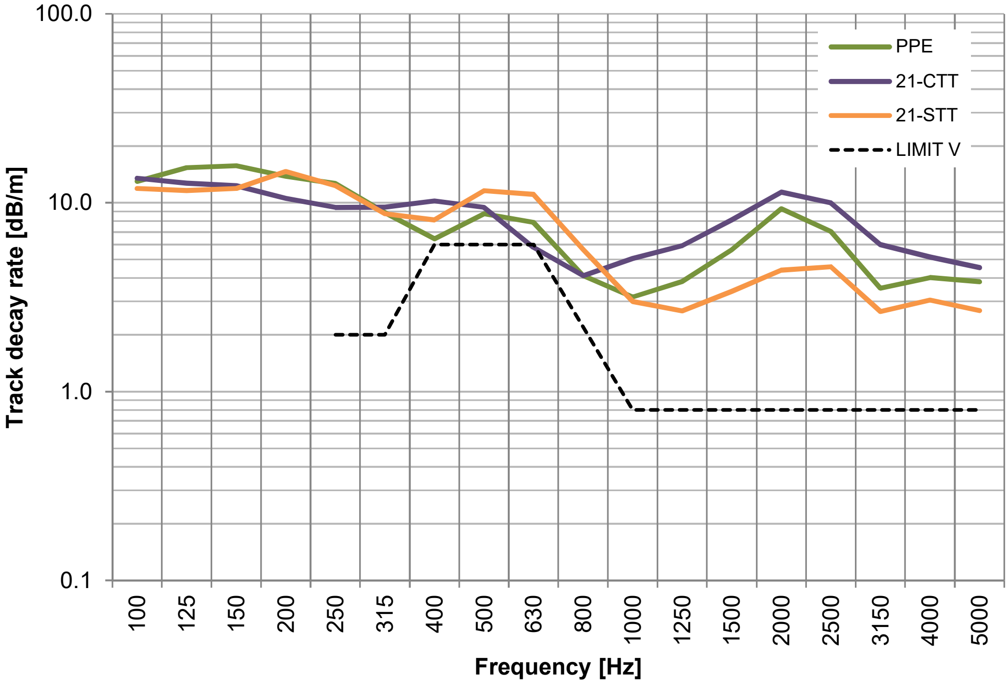

Figure 9. Track decay rate for all sub-sections in vertical direction.

4.3. Noise measurements

As proposed by the European standard [11], time signals of sound pressure recorded during tram TMK2266 pass-by have been expressed as sound pressure level in dB with the reference value $p_0 = 20$ μPa. Equivalent sound pressure level has been calculated for whole vehicle pass by to conduct comparison of different test sections. Equivalent sound pressure level is expressed as

$$L_{pAeq,Tp} = 10\log\left(\frac{1}{T_p}\int_0^{T_p}\frac{p_A^2(t)}{p_0^2}\right)\ [dB] \tag{3}$$

where $L_{pAeq,Tp}$ is the A-weighted equivalent continuous sound pressure level in dB; T_p is the measurement time interval in s; $p_A(t)$ is the A-weighted instantaneous sound pressure at running time t in Pa; and p_0 is the reference sound pressure ($p_0 = 20$ μPa).

Recorded sound pressure levels of 2 pass-by at each test sub-section has been recorded for tram TMK2266 pass-by at 30 km/h and the average value expressed as final equivalent noise level, Table 2.

Table 2. Equivalent sound pressure levels on test section.

Test section	$L_{pAeq,Tp}$ [dB]	SD
PPE	84.5	0.3
21-CTT	80.9	1.4
21-STT	82.9	0.8

It is obvious that under the same conditions (constant speed, low ambient noise, same tram vehicle), newly designed tram tracks perform better from the vibro-acoustic point of view. Noise reduction of 1.6 dB is recorded on Zagreb 21-STT section and 3.6 dB on Zagreb 21-CTT section.

5. Conclusion

Due to high traffic loads, tram tracks in the City of Zagreb are exposed to high stresses, they rapidly degrade and deteriorate. To answer the harsh tram traffic operation conditions, and to optimize maintenance procedures, two new solutions for rail fastening systems were developed, named 21-CTT 21-STT systems. The main objective in developing the new systems was to develop a tram track structure which would be quick and simple to construct, have longer exploitation life, be easy to maintain, and have good exploitation characteristics.

Measurements conducted on test section in Savska street give an opportunity to evaluate the newly designed tracks. The new tracks, especially 21-STT shows improved performance in load distribution. Combined with fast construction (by using pre-fabricated and pre-assembled components) and low construction cost it is a great alternative when considering construction of new tram tracks. For reconstruction of current tram tracks 21-CTT system that is based on standard fastening system typically used in Zagreb, brings an improvement in component availability, stray current insulation as well great noise and vibration attenuation.

Track decay rate determination using vehicle pass-by method has been proven as a very reliable and practical method to measure vibro-acoustic performance of tramway tracks.

Two procedures, track decay rate measurements and noise measurements using vehicle pass-by have confirmed track contribution to overall noise levels is highest on referent track PPE, lower on stiffer 21-STT with direct elastic fastening and significantly lower on 21-CTT.

References

[1] Directive 2002/49/EC of the European Parliament and of the Council relating to the assessment and management of environmental noise, *Off. J. Eur. Communities 2002* Available at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2002:189:0012:0025:EN:PDF
[2] European Committee for Standardization (CEN) 2003 Mechanical vibration and shock - evaluation of human exposure to whole-body vibration - Part 2: Vibration in buildings (1-80Hz) (*EN ISO 2631-2:2003)*
[3] Hemsworth B 2013 *Strategies and Tools to Assess and Implement Noise Reducing Measures for Railway Systems (STAIRRS) - Final technical report*
[4] Ahac M 2013 *Mechanical-empirical model for tram track gauge deterioration during exploitation - Doctoral thesis* (University of Zagreb)
[5] Thompson D J and Jones C J C 2000 A Review of the Modelling of Wheel/Rail Noise Generation *Journal of Sound and Vibration* **23**1(3) pp 519–36
[6] Jones C J C, Thompson D J and Diehl R J 2006 The use of decay rates to analyse the performance of railway track in rolling noise generation *Journal of Sound and Vibration* **293**(3–5) pp 485–95
[7] European Committee for Standardization (CEN) 2008+2010 Railway applications - Noise emission - Characterisation of the dynamic properties of track sections for pass by noise measurements *(EN 15461:2008+A1:2010)*
[8] Haladin I, Lakušić S and Košćak J 2016 Measuring vibration damping level on conventional rail track structures *Gradjevinar* **68**(6)
[9] European Committee for Standardization (CEN) 2016 Railway applications - Acoustics - Measurement method for combined roughness, track decay rates and transfer functions *(CEN/TR 16891)*
[10] Lakušić S, Haladin I and Ahac M 2016 The Effect of Rail Fastening System Modifications on Tram Traffic Noise and Vibration *Shock and Vibration* **4** pp 1–15
[11] International Organisation for Standardization (ISO) 2013 Acoustics – Railway applications – Measurement of noise emitted by railbound vehicles *(ISO 3095)*