DOI: https://doi.org/10.14256/JCE.3368.2021

Građevinar 1/2022

Primljen / Received: 29.9.2021.
Ispravljen / Corrected: 28.1.2022.
Prihvaćen / Accepted: 31.1.2022.
Dostupno online / Available online: 10.2.2022.

Evaluation of non-acoustic properties of traffic noise walls

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Subject review

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The presented research aims to reduce the uncertainty in the selection of noise wall panel materials, and thus to improve the traffic noise management process in the Republic of Croatia. An evaluation of concrete, metal, wood, and transparent panels is performed to improve the panel material selection procedure in the planning and design of traffic noise walls. Properties of panels made of these four basic materials are studied under the assumption that the acoustic requirements relating to the wall structure have been fully met. Thus, the research focuses on six non-acoustic properties of panels (criteria that must be considered by civil engineers): mechanical resistance and stability, service life, construction, maintenance, and replacement costs, service life costs, and recyclability. These properties are analysed using the publicly available data from secondary sources. The data are systematized and subjected to a multicriteria analysis, which has revealed that concrete panels have the highest (weighted and unweighted) mean score.

Key words:

noise protection, mitigation measures, planning, design, panel material, multicriteria analysis

Pregledni rad

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Vrednovanje neakustičnih svojstava zidova za zaštitu od prometne buke

Cilj prikazanog istraživanja bio je smanjiti nesigurnost u odabiru materijala panela ispune zidova za zaštitu od buke i time unaprijediti proces upravljanja prometnom bukom u Republici Hrvatskoj. Radi unaprjeđenja postupka odabira materijala panela ispune pri planiranju i projektiranju zidova za zaštitu od prometne buke, izvršena je evaluacija betonskih, metalnih, drvenih i prozirnih panela. Istraživanje svojstava panela izrađenih od ta četiri osnovna materijala provedeno je uz pretpostavku da su akustični zahtjevi na konstrukciju zida potpuno zadovoljeni. Tako je istraživanje moglo biti usmjereno na šest neakustičnih svojstava panela (kriterija koja su inženjeri građevinarstva dužni razmatrati): mehaničku otpornost i stabilnost, trajanje, troškove građenja, održavanja i zamjene, troškove uporabljivosti i reciklabilnost. Analiza navedenih svojstava provedena je nad prikupljenim javno dostupnim podacima iz sekundarnih izvora. Podaci su sistematizirani te podvrgnuti više kriterijskoj analizi koja je pokazala da betonski paneli imaju najveću (ponderiranu i neponderiranu) srednju ocjenu.

Ključne riječi:

zaštita od buke, mjere zaštite, planiranje, projektiranje, materijal panela zida, višekriterijska analiza

1. Introduction

According to the data published by the European Environment Agency (EEA), noise pollution in Europe constitutes a significant health and environmental hazard [1] that causes sleep [2] and study [3-6] disorders, high blood pressure and ischaemic heart disease [7-9], while producing the highest levels of disturbance to the communication and cognitive processes [10, 11]. According to the European Directive relating to the assessment and management of environmental noise 2002/49/EC (END), the EU member countries are required to determine exposure of population to excessive levels of noise generated by the main transport facilities and the industry based on strategic noise maps [12]. These strategic noise maps serve as the basis for preparing, adopting, and publishing action plans for the management of environmental noise and its harmful effects, also including the noise mitigation measures specified on the national level [12, 13]. According to the most recent data published by the European Environment Agency, the road and railway traffic noise is still the dominant source of traffic noise, both in urban and rural areas. Approximately 125 million of the EU residents are exposed to the total road traffic noise levels larger than 55 dB(A), while additional 12 million are exposed to the total road traffic noise levels exceeding 65 dB(A) [14]. Although road traffic is the most significant source of environmental noise in Europe (compared to rail traffic, ten times more people are exposed to road traffic noise), the levels of noise produced by railway traffic are often higher.

Over the past several years, action plans have been aimed at raising awareness about the noise as an environmental problem, and at promoting implementation of measures for noise reduction at the source. For road traffic, this involves promotion of the use of electrical vehicles, vehicles with more silent engines and tyres, replacement of standard pavements with silent ones, and implementation of "unpopular" traffic regulation measures like limiting speed and access to infrastructure. Measures aimed at reducing the rail traffic noise emissions are focused on the vehicle (ensuring smoothness of wheels, installation of less noisy disk brakes) and the track (ensuring smoothness of rails, installation of elastic rail fastening systems, sleepers with elastic setting pads or setting pads made of composite materials, lining the track with absorbing plates, lining the rail web with elastic elements) [15]. Despite significant advancements made in the efficiency and the use of measures for mitigating road and rail traffic noise at the source, more than 25 % of newly planned measures are aimed at reducing propagation of sound waves [14], mostly through construction of noise barriers between the source and the recipient of noise.

The first use of noise barriers dates to more than fifty years ago both in the USA and in Europe [16, 17]. The term "noise barrier" or "noise screen" denotes various structures that are destined for reducing noise levels. Standard types of noise barriers that are placed along roadways are earth embankments, noise walls, and their combinations [18]. The research described in this paper focuses on noise walls. These are slender linear structures that are mostly used at the existing transport facilities [19] where space for barriers is limited. The walls consist of panels horizontally arranged between steel or concrete posts. The H-posts are anchored onto the existing structures (walls, parapets) or have their own foundations (piles, strip, or isolated foundation footings).

When selecting panel materials, one can choose between a wide array of products that are classified according to their acoustic properties (absorbing or reflecting), according to transparency level (transparent or nontransparent), and according to dominant material used in their fabrication. For the purpose of this research, the panels have been systematized into four groups according to the dominant material: (1) concrete, (2) metal, (3) wooden, and (4) transparent materials (e.g., polymethacrylate). The choice of materials for noise walls is influenced by a number of factors, i.e., in addition to acoustic efficiency of a certain panel type, the choice of material also depends on physical dimensions of the wall, on the applicability of the panel at a particular location, on local environmental conditions, and also on aesthetic requirements including local architectural considerations, perception and acceptance of the structure by the public, traffic safety (i.e. problem of visibility at intersection zones), and price [20, 21].

During selection process of panel material, it is advisable to analyse not only acoustic but also technological and economic properties of walls, so that an optimum long-term protection can be ensured [22, 23]. Despite significant experience in the use of noise walls, designers are still faced with several unknowns relating to the behaviour of walls during their service life [24], including their stability, durability, fire resistance, resistance to impact, and atmospheric influences. The principal dilemma is how will the unavoidable degradation of panels influence the efficiency and long-term sustainability of noise walls at a particular location and under local conditions. We tried to answer this question in our earlier research [25], where we quantified results of multicriteria analyses of the publicly available meta-data about the concrete, metal, and wooden wall panels, with the objective of obtaining information about their acoustic and technical performance, as well as about their long-term sustainability and safety. The research in this area was conducted to:

- reduce the level of uncertainty during selection of material for noise walls in the design process
- support the process of managing traffic noise protection measures by shifting the emphasis from the panel procurement price (being the main panel material selection criterion in south-eastern European countries) to their durability and sustainability.

This paper presents a continuation of the study on the noise protection processes utilised along the road and railway networks of the Republic of Croatia (RH), including properties of the concrete, metal, wooden, and transparent noise wall panels that are currently in use. The panel evaluation procedure was conducted based on the publicly available data from secondary sources, under the assumption that basic acoustic requirements relating to the wall structure had been fully met. The principal objective of the research is to evaluate the panels by considering their non-acoustic properties: mechanical resistance and stability, shortest service life, average construction, maintenance, and replacement costs, service life costs, and potential recyclability of the end-of-life panels. The systematization of the international research results, and the results of our own analysis and assessment of non-acoustic properties of panels, will contribute to the adoption of additional pointers - durability and sustainability of panels - in the process of the planning and design of noise walls along the road and railway network.

2. Protection from road and railway traffic noise in Croatia

Environmental noise is regulated in the Republic of Croatia by the Noise Protection Act (Official Gazette Nos.: 30/2009, 55/2013, 153/2013, 41/2016, 114/2018, and 14/2021) [26], which is transposed from the Environmental Noise Directive (END). The said Act defines measures aimed at avoiding, preventing, or mitigating harmful effects to human health as caused by environmental noise, including disturbance by noise. The measures are implemented by determining exposure to environmental noise through preparation of strategic noise maps based on noise assessment methods, by making noise data available to public and, finally, through preparation and publication of action plans based on strategic noise maps.

Strategic noise maps are prepared using computation methods to calculate noise emissions and noise propagation from known sources of noise (road traffic, railway traffic, air traffic, and industrial plants and facilities) through geographic areas. Strategic noise maps form a professional basis for the preparation of physical development plans. They are a useful instrument for environmental noise management that enables the preparation of action plans, more efficient land use planning, planning protection of the existing areas from noise sources, implementation of acoustic planning, and assessment of exposure of population to excessive noise levels. Strategic noise maps are continuously updated in accordance with physical changes and they must be renewed or prepared every five years. Strategic noise maps are collected and registered under the authority of the Croatian Ministry of Health, which submits this information to the European Commission through the EIONET system operating in the scope of the European Environment Agency (EEA).

The objective of the noise protection action plans is to plan - based on strategic noise maps - the ways in which exposure of population to excessive noise will be reduced, to define the time schedule for implementing noise protection measures and, finally, to estimate the effects of these measures. It is specified in the Noise Protection Act [26] that noise protection must be implemented round-the-clock (24 hours a day), where the “day” period lasts 12 hours, from 7 a.m. to 7 p.m., the “evening” period lasts 4 hours, from 7 p.m. to 11 p.m., and the “night” period lasts 8 hours, from 11 p.m. to 7 a.m. According to the Byelaw for the preparation of strategic noise maps [27], a noise indicator (acoustic value used for describing environmental noise that is related to harmful effects of noise) is used for the “day-evening-night” period Lden, and an additional indicator is used for the “night” period Lnight, both values being expressed in dB(A). According to the END, the top value of Lden for the estimation of disturbance is set to 55 dB(A), while the top value of Lnight for the estimation of sleep disturbance amounts to 50 dB(A). In addition to the above indicators, the noise level indicator for the “day” period Lday, and the noise indicator for the “evening” period Levening, are also used for the acoustic planning and determination of noise protection areas.

The Noise Protection Act also defines the subjects that must prepare strategic noise maps, as well as the subjects that are required to prepare and publish action plans enabling management of environmental noise and its harmful effects, including noise protection measures. Thus, strategic noise maps and action plans have to be prepared by cities having more than one 100,000 inhabitants, as well as by owners or concessioners of industrial areas, major roads with annual traffic flow of more than three million vehicle passages a year, major railways with more than 30,000 train passages per year, and major airports with more than 50,000 operations (take-offs or landings) per year [26]. In compliance with obligations specified in the Noise Protection Act, and based on the data available in 2016, strategic noise maps and action plans were prepared for:

- City of Zagreb (ZG), City of Split (ST), City of Rijeka (RI), and City of Osijek (OS);
- major road sections operated by Croatian Highways (HAC) for the motorway areas A1, A3, A4 and A11; Rijeka-Zagreb Motorway (ARZ), added to HAC as from 1 January 2020, for the A6 motorway areas; Zagreb-Macelj Motorway (AZM) for the A2 motorway areas; Bina-Istra for the A8 and A9 motorway areas; Croatian Roads (HC) roads and county roads situated in the Istrian County, Primorje-Gorski Kotar County, and Split-Dalmatia County;
- major railway sections operated by HŽ Infrastruktura (HŽI) in the railway areas of significance for international transport: M101 National Border - Savski Marof - Zagreb Central Train Station, and M102 Zagreb Central Train Station - Dugo Selo.

Strategic noise maps and action plans, prepared in accordance with the Noise Protection Act, are an integral part of the Environmental Protection Information System (ISZO RH) that has been set up and is being developed, coordinated, and maintained, by the Croatian Agency for the Environment and Nature in compliance with the Environment Protection Act (Official Gazette 80/13) and the Ordinance on the environmental Protection Information System (Official Gazette 68/08). The information system encompassing strategic noise maps and action plans, prepared by the Agency for the Environment and Nature in consultation with the Ministry of Health, is a publicly available portal (buka-porta.azo.hr).

The results obtained by analysing the data on the number of inhabitants exposed to excessive noise levels, published on the said portal in May 2021 and presented in Figure 1, show that the frequency of exposure of the Croatian population as related to the noise source (road or railway traffic) and location of the source (in urban or rural areas), generally coincides with the trends registered throughout the EU. Road traffic is the dominant source of sleep disturbance and disruption in Croatia, and the problem of exposure to road traffic noise is much more pronounced in urban areas. The number of residents exposed to excessive road traffic noise levels is also by about ten times greater compared to the number of residents exposed to excessive rail traffic noise levels. The exposure to excessive rail traffic noise levels is similar in urban and rural areas, i.e., it is independent of the location of the railway. In rural areas, and for noise indicators greater than 65 dB(A), the railway traffic noise problem is greater compared to the noise generated by road traffic.

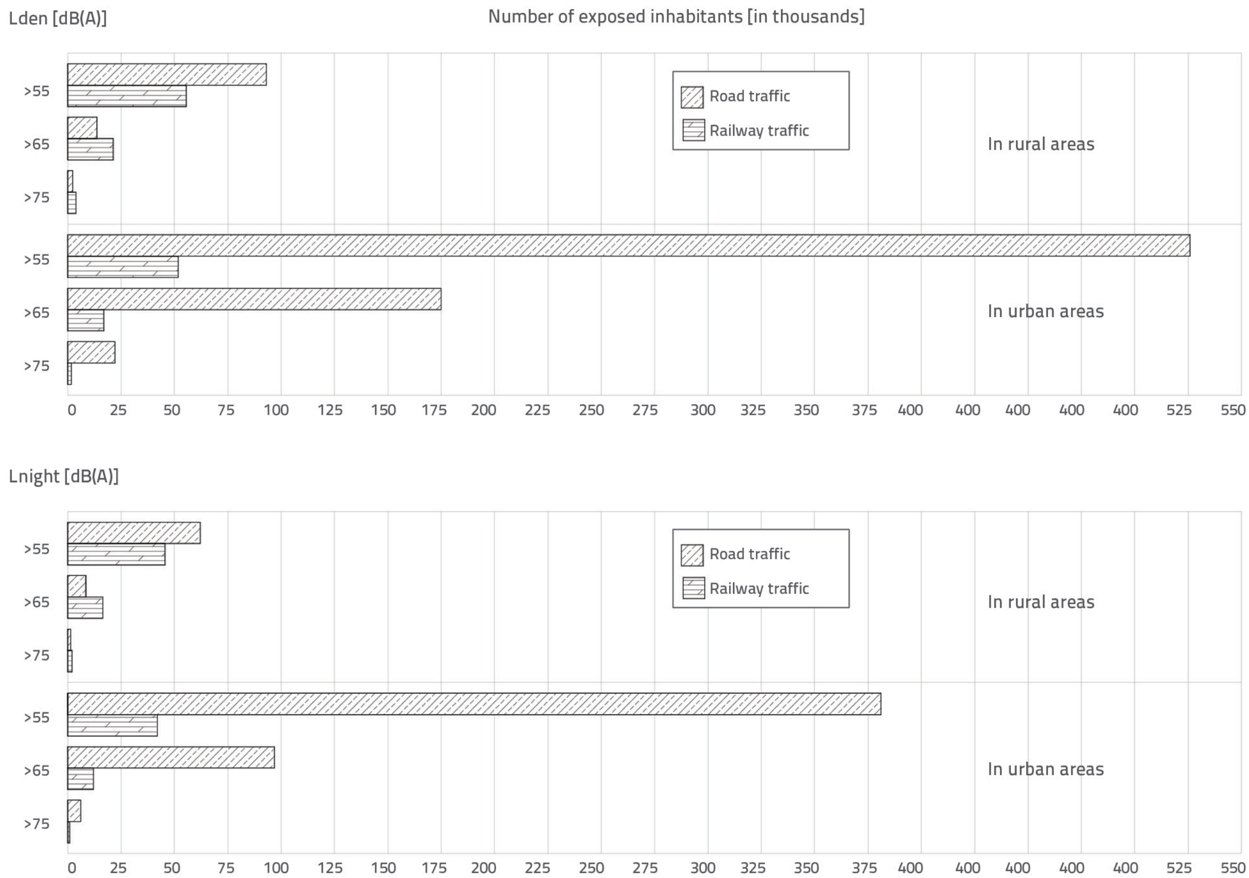

Figure 1. Number of inhabitants exposed to excessive road and rail traffic noise levels, based on results presented in strategic noise maps

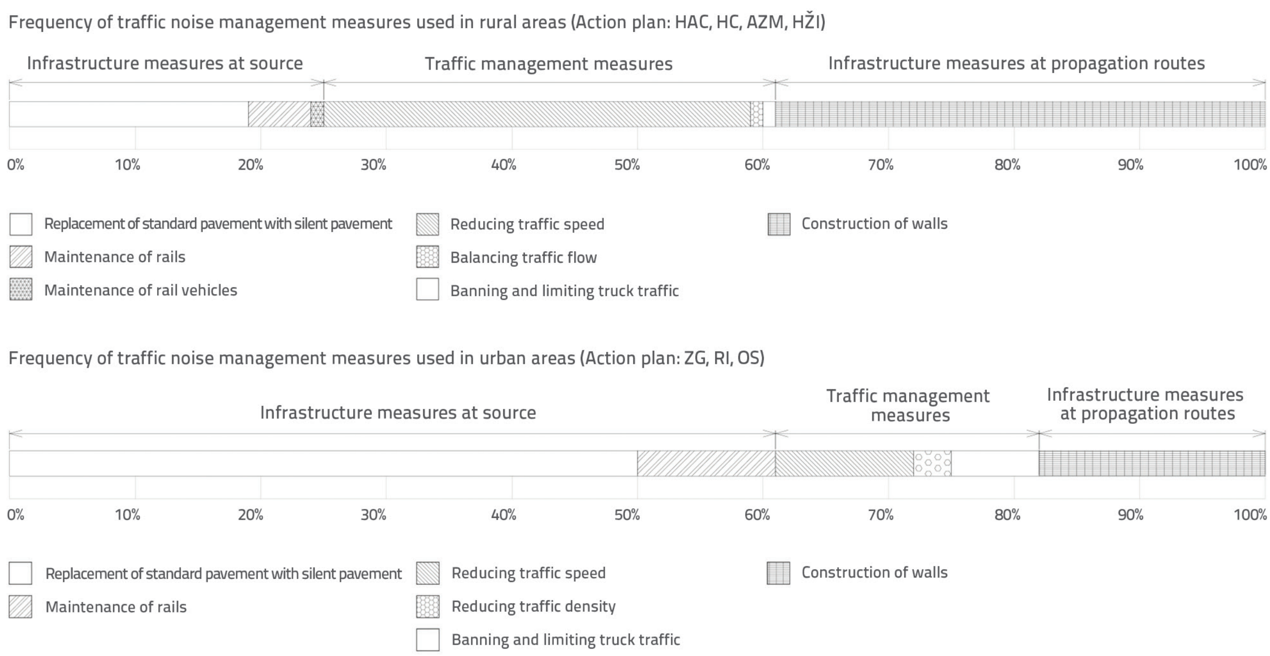

Figure 2. Frequency of traffic noise management measures specified in Action Plans, as applied on the road and rail network in Croatia

The frequency of planned rail and road traffic noise protection measures in the areas in which strategic maps point to the need for noise management (Figure 2) was determined by analysis of the publicly available noise management action plans prepared for four concessioners of major roads and railways (HAC, AZM, HC, and HŽI) and for three cities (ZG, RI, OS). As the space for realisation of noise barriers is often insufficient in urban areas, the most frequent measure implemented in such areas (planned at 50 % of identified areas) involves replacement of the standard pavement with the silent pavement. Other measures focusing on the source of noise (namely, keeping the driving surface smooth and flat, proper traffic management) are planned on a total of 32 % of the area, while realisation of noise walls is planned at the non-negligible 18 % of the area requiring noise management. A much different protection concept is specified in the action plans for rural areas. Thus, in rural areas the noise management along the road and rail infrastructure involves realisation of walls in as many as 39 % of the cases.

Strong capital investments that are to fully modernise the entire transport infrastructure in Croatia are planned over the next period. These investments will be realised partly through the Recovery and Resilience Mechanism and partly through the new operational programme. Therefore, in addition to the planned implementation of measures for the reduction of the existing traffic noise levels through action plans, an intensive increase in the awareness of the need to protect population living alongside the road and rail infrastructure can also be expected, especially in the zones outside the four greatest cities. The reason for this is that, according to the Byelaw on maximum allowable noise levels in places where people work and stay (Official Gazette 145/2004) [28], which was in use until the end of December 2021, i.e., until entry into force of the Byelaw on maximum allowable noise levels with respect to the type of noise source, and the time and place of noise generation (Official Gazette 143/2021) [29], the new transport infrastructure facilities (railways, national roads, and county roads in urban areas) which touch upon or intersect the zones destined for (1) recovery and medical care, (2) solely for habitation and living, (3) mixed, mostly residential use, (4) mixed, mostly commercial (with some residential) use, should be designed and built in such a way that the noise level at the boundary of the corridor of such infrastructure facilities does not exceed the equivalent noise level of 65 dB(A) during the day, or 50 dB(A) during the night. In addition, in the case of reconstruction or adaptation of transport facilities, which would generate noise exceeding the specified levels, it will be necessary to design or reconstruct or alter these transport facilities in such a way that the noise level at their corridor boundary is reduced to the level of 65 dB(A) during the day, and 50 dB(A) during the night. According to the Byelaw adopted in 2021 [29], the procedures initiated based on the Byelaw adopted in 2004 [28] will be completed as specified in the byelaw adopted in 2004. Furthermore, Decisions on the implementation of noise protection measures issued based on noise measurements according to the Byelaw [28] will remain in force until the change of the noise sources indicated in such Decisions on the implementation of noise protection measures. Regarding implementation of noise protection relating to road and rail infrastructure facilities, the changes brought by the new 2021 Byelaw include the following [29].

- Maximum allowable rated noise levels have been introduced for the period "evening", which are equal to the values for the period "day" in all zones except in zone 1, where this value has been reduced to 45 dB(A).
- Maximum allowable daily noise levels Lden have been introduced for zones 1 through 5, amounting to 50, 56, 57, 66, and 67 dB(A), respectively.
- The definition of zones with the highest allowed rated noise levels has been extended. The definition concerning zone 1 has been extended by adding the following areas: national parks, special reserves, nature parks, regional parks, nature monuments, significant landscapes, park-forests, park architecture monuments, and silent areas outside of urban areas. Former zone 5 (zone with commercial occupancy - manufacturing, industry, warehouses, repair, and servicing shops [28]) is now divided into zones 5 and 6 as follows. Zone 5 includes zones of economic activity (mostly finishing trades), zones of commercial activity (mostly involving provision of services and commercial activity, and commercial or municipal services), zones for food service establishments and tourism, land, sea, and river-oriented sports and recreation zones as well as ports for nautical tourism. Zone 6 includes zones of economic activity (mostly manufacturing and industrial activities), zones with seaports of national significance for crucial activities, zones with seaports of special international economic significance, zones with seaports of county-level significance, and zones with river ports of national and county-level significance. At that, the maximum allowed rated noise level (defined as the total noise immission from all existing and planned noise sources together) for zone 5 amounts to 65 dB(A) for the day and evening periods, and to 55 dB(A) for the night-time period. As to zone 6, the level of noise originating from the noise source within this zone at the boundary with the closest zone 1, 2, 3 or 4 in which the highest noise immission is expected, must not exceed allowable noise levels at the boundary with the zone 1, 2, 3 or 4.
- As to newly constructed infrastructure facilities that touch upon or intersect with zones 1-5, the highest allowable daily noise levels Lden of 66 dB(A) have been set for the traffic corridor boundary.
- For the areas in which the existing level of residual noise is equal to or higher that the allowed rated noise level, the immission of noise that would be generated by the newly-designed, constructed or reconstructed or altered structures with the corresponding noise sources, must not exceed allowable levels reduced by 5 dB(A), while areas in which the existing level of residual noise is lower than the allowed grade noise level, the immission of noise that would be generated by the newly-designed, constructed or reconstructed or altered structures with the corresponding noise sources, must not increase the existing noise levels by more than 1 dB(A).

Based on the trend observed in Croatia regarding the selection of traffic noise protection measures, it can be concluded that noise level restrictions at the traffic corridor boundaries of newly constructed and reconstructed road and rail transport facilities, as set in Byelaws

[28, 29], will certainly require a more intensive use of noise walls. Although they are still regarded as traffic equipment, the fact is that noise walls, when compared to other big structures, require equal quantities of resources, and have an equal effect on the built environment. That is why a considerable attention must be paid to the selection of the panel material when planning and designing noise walls. According to [30], in southern EU countries, the cost of realisation is usually the decisive factor in the design of noise walls, i.e., an advantage is most often given to less costly panels. This is hardly surprising as an average price of installation (assembly) of a square meter of panels of the cheapest wall alternative - wall with wooden panels - amounts to approximately € 120 [31]. This price leads to a total cost of approximately € 2 million for walls realized on both sides of the transport facility in a total length of four kilometres, with an average height of four meters. On the other hand, international experience shows that, when selecting the material, an emphasis should be placed on the selection of panels of highest durability in order to achieve long-term sustainability of this noise protection measure. It can be said that, if basic conditions ensuring acoustic efficiency of walls as to noise protection are fulfilled - the wall is sufficiently high to break the line of sight toward the noise source, the required density of panel is acoustically satisfactory, and there are no openings in panels or between panels that would allow the passage of sound waves [32] - a rational decision on the selection of panel material should be made through the control of costs not only relating to construction of noise walls, but also relating to their maintenance and removal [24]. Therefore, already at the stage of planning allocation of funds and preparing design documents, infrastructure operators and designers must have all relevant information about properties of the panels to be used in the construction of walls, so that they can reach a sound decision that will prove satisfactory in the long run.

ROAD SECTOR CEN/TC 226/WG 6 Road traffic noise reducing devices		**RAILWAY SECTOR** CEN/TC 256/SC 1/WG 40 Noise barriers and related devices acting on airborne sound propagation	
Specifications	EN 14388:2015	Technical specifications for interoperability (TSI) of subsystems "rolling stock – noise"	COMMISSION REGULATION (EU) br. 1304/2014
TEST METHODS FOR DETERMINING ACOUSTIC PERFORMANCE			
Intrinsic characteristics of airborne sound insulation under diffuse sound field conditions	EN 1793-1:2017	Intrinsic characteristics – Sound absorption in the laboratory under diffuse sound field conditions	EN 16272-1:2012
Intrinsic characteristics of airborne sound insulation under diffuse sound field conditions	EN 1793-2:2018	Intrinsic characteristics - Airborne sound insulation in the laboratory under diffuse sound field conditions	EN 16272-2:2012
Normalised traffic noise spectrum	EN 1793-3:1997	Normalised railway noise spectrum and single number ratings for diffuse field applications	EN 16272-3-1:2012
Intrinsic characteristics -- In situ values of sound diffraction	EN 1793-4:2015	Normalized railway noise spectrum and single number ratings for direct field applications	EN 16272-3-2:2014
Intrinsic characteristics - In situ values of sound reflection under direct sound field conditions	EN 1793-5:2018	Intrinsic characteristics - In situ values of sound diffraction under direct sound field conditions	EN 16272-4:2016
		Intrinsic characteristics - In situ values of sound reflection under direct sound field conditions	EN 16272-5:2014
Intrinsic characteristics - In situ values of airborne sound insulation under direct sound field conditions	EN 1793-6:2018	Intrinsic characteristics - In situ values of airborne sound insulation under direct sound field conditions	EN 16272-6:2014
		Extrinsic characteristics - In situ values of insertion loss	EN 16272-7:2015
NON-ACOUSTIC PROPERTIES			
Mechanical performance and stability requirements	EN 1794-1:2018	Mechanical performance under static loadings -- Calculation and test methods	EN 16727-1:2018
General safety and environmental requirements	EN 1794-2:2011	Mechanical performance under dynamic loadings due to passing trains -- Resistance to fatigue	EN 16727-2-1:2018
Reaction to fire - Burning behaviour of noise reducing devices and classification	EN 1794-3:2016	Mechanical performance under dynamic loadings caused by passing trains - Calculation method	EN 16727-2-2:2016
		General safety and environmental requirements	EN 16727-3:2017
PROCEDURES FOR ASSESSING LONG-TERM PERFORMANCE			
Acoustical characteristics	EN 14389-1:2015	Acoustical characteristics	EN 16951-1:2018
Non-acoustical characteristics	EN 14389-2:2015	Non-acoustical characteristics	EN 16951-2:2018

Figure 3. Structure and content of European standard packages relating to devices for reducing noise in rail and road traffic

3. Overview of required panel properties

When designing barriers for the protection against noise generated by the road and rail traffic, all EU members are required to respect CEN/CENELEC Internal Regulations of the European standards relating to the noise reduction devices that curb propagation of sound through air. These are CEN / TC 226 / WG6 introduced in 1989 for the road sector and CEN / TC256 / SC1 / WG40 introduced in 2008 for the railway sector. Both packages can be divided into three basic categories: acoustic properties, non-acoustic properties (mechanical properties, resistance and stability of structures, safety, and resistance to fire), and long-term properties (barrier efficiency), Figure 3. All standards presented in Figure 3 have been included in the Croatian standardisation system and are considered in the scope of technical committees HZN TO 509 (Road equipment) and HZN TO 528 (Railway equipment).

The following text briefly describes basic structural requirements for noise walls, and provides conclusions, based on consultation of the available data, about general influence of panel properties on the efficiency, stability, safety, and durability of noise walls.

3.1. Acoustic properties

The efficiency of noise walls in the reduction of traffic noise levels depends on a considerable number of parameters: acoustic properties of panels and material they are made of, wall dimensions, position of the noise source, wall and receiver, traffic intensity and speed, type and condition of vehicles, condition of the driving surface, characteristics of the terrain between the source and the receiver, and weather conditions [20]. Basic parameters describing acoustic properties of the wall panels are the sound absorption and the sound insulation, and the factors having the greatest influence on these parameters are the distance of walls from the noise source, the wall height, and the thickness and type of panel material [33], i.e., the density and porosity of panels [34].

The greater the sound absorbing capacity of the wall panels, the smaller the reflection of sound waves from the wall toward the objects on the opposite side of the transport facility and back toward the vehicle (noise source). Non-absorbing or reflecting panel can cause the sound wave to pass above the wall after it has been reflected multiple times between the panels and the vehicle. Because of such behaviour of sound waves, the use of panels with low or no absorption properties can additionally increase the level of noise at the receiver positions. An increase in the level of noise due to reflection can attain up to 3 dB(A) [20]. This problem is the most pronounced in the case of transparent reflecting panels placed on both sides of the transport facility as the panels create the so called "canyon" effect, which can increase the noise level for 6 dB(A) [35].

The sound insulation capacity is primarily dependent on the weigh and density of panels. The panel is considered to have sufficient insulating properties if its density amounts to at least 15 kg/m^3 [18]. In addition, any wall panel material whose weight amounts to at least 20 kg/m^2 enables realisation of sound insolation amounting to 20 dB(A). Additional reduction of 1.5 dB(A) can be achieved with every additional meter of the wall height [34].

The wall durability and its acoustic properties are two highly interdependent characteristics. As a rule, durable products always fulfil acoustic requirements as their weight and density, in addition to durability, also ensure achievement of the required sound insulation [36].

Table 1 shows the lowest recorded absorption and sound insulation values of noise walls with concrete, metal, wooden, and transparent panels, as presented in [37, 38].

3.2. Non-acoustic properties

Required general non-acoustic properties of noise walls are their (1) mechanical resistance and stability - under static and dynamic load (caused by the wind, the passage of vehicles, and by drifts of snow cleaned from the traffic surface), under impact load due to airborne fragments and materials from the traffic surface, and under fatigue load; (2) compliance with general safety requirements and environmental protection conditions - resistance to fire, generation of fragments, environmental protection, emergency exits, reflection of light, transparency; (3) reaction to fire - behaviour when burning, density of smoke and harmful gases [32, 39].

Permanent load, i.e., the weight of panels, must be considered during the analysis and design of all wall types. The weight of panels is especially important when designing walls on structures (viaducts, bridges, retaining walls, and abutment walls) and, if it becomes necessary to apply heavier panels to achieve the required insulation property, this weight of the panels might even impose the need to change the design of the load bearing structure. That is why lighter panels are in most cases selected, regardless of their insulation property, when the walls are realized on the existing structures on which the modifications that would ensure their greater load bearing capacity cannot be made.

In addition to permanent load in the form of panel weight, the greatest load such structures must withstand is the load caused by wind action. The wind load depends on the geographical location of the wall and may also depend on the relationship between the altitude of the locality and the surrounding topography. This load affects the overturning moment or the rotational force acting on the wall, its foundations, and piers. However, unlike the permanent load, the wind load does depend on the type of material the panels are made of.

Table 1. Acoustic properties of noise protection walls

Property	Concrete panels	Metal panels	Wooden panels	Transparent panels
Sound absorption [dB(A)]	≥ 4	≥ 8	≥ 8	< 4
Sound insulation [dB(A)]	≥ 15	≥ 15	> 24	> 24

Aerodynamic load must be considered if the walls are placed along the infrastructure that is destined for the traffic of heavy vehicles at high speeds. In such cases, the wall can be subjected to significant dynamic pressure due to circulation of air. For instance, vehicles operating at a speed of 100 km/h can cause the difference in pressure of ±0.5 kN/m^2 at the wall located 3 metres away from the vehicle [20]. Much greater changes in pressure can be expected in the immediate vicinity of tunnels. This load must be considered when designing and selecting a method for fastening the absorbing layers of wall panels.

Snow load is the horizontal load caused by snow accumulated along the bottom surface of the wall. When designing the walls, one should not only consider their size (dimensions) in relation to snow load, but also the space necessary for the safe disposal of snow drift cleaned from the traffic surface, as well as the safe distance of the wall structure from the manoeuvring space of the snow clearing machine.

The impact load is the load generated by vehicle impact and by fragments and materials carried through air from the traffic surface. The walls are in most cases not designed to withstand the force of direct impact by vehicles, so this protection is ensured by installing traffic barriers next to or on such walls, except in cases when the noise wall also serves as a traffic barrier.

Fire resistance should be considered by setting limitations to the use of materials, both flammable and non-flammable, that could generate toxic gases or flying embers in the contact with open fire, as a consequence of forest fires or traffic accidents.

At the design stage, it is also necessary to consider the hazard from falling fragments if the panels are installed on the structures of bridges or viaducts. It is also necessary to plan exits for emergency situations and for the maintenance of walls in the case of the walls exceeding 500 m in length, all in accordance with regulations for tunnels [40].

The light reflecting from the smooth panels of the noise walls, i.e., the reflections that can disturb infrastructure users, constitute a considerable safety problem in the case metallic or transparent panels are applied. This negative phenomenon is even more pronounced when lighter-coloured panels are used, and it can occur both during the day (in morning or evening hours when sun rays are at a sharp angle) and during the night because of the use of headlights, which is especially noticeable if the panel surface is wet. This problem can be eliminated or reduced by using panels with rougher surface and deep relief-type indentations [20, 22].

As to the long-term non-acoustic efficiency, the material selection and structural shaping must be conducted to ensure the greatest possible durability of the structure exposed to weather influences and climate changes, the longest possible service life with minimum or no maintenance, and an efficient recovery of the end-of-life structure [32]. At that, the quantity of work and the cost of panel maintenance will greatly influence the sustainability of the walls and the environmental impacts on the walls throughout their service life. The service life of a noise wall can be defined as a "care-free period" during which the wall will continuously and optimally fulfil its functions without greater changes of it properties, i.e., it is the time from its construction to the moment when the wall panel has to be replaced [24]. This time will depend on the material the panel is made of, and the selection of an appropriate material will primarily depend on requirements the designer has to respect so as to meet technical objectives that will ensure long service life of the panel under local conditions. At that, it is important to consider the long-term resistance of the material to the phenomena and processes next to and on the transport facility, such as chemical substances, de-icing salt, dirty water or dust, dew, freezing and thawing processes, temperature extremes, UV radiation, vibrations generated by traffic, biological processes, and similar occurrences. The resistance of walls to weather conditions will influence their acoustic and non-acoustic properties and will define how often the walls will require greater repairs or replacement. It should however be noted that, at this time, there are no data about research that would focus on the influence of weather conditions on wall panels made of various materials [32].

4. Non-acoustic properties of noise wall panels

A systematized overview of basic properties of concrete, metallic, wooden, and transparent panels (usual panel composition, location and frequency of use, transport and installation possibilities, maintenance requirements, and recovery options) is given in this section. The overview is based on the analysis of publicly available research results and technical information about physical properties, long-term performance, and technical and economic sustainability of noise walls, as presented in [16, 24, 32, 33, 38, 41, 42, 43, 44]. Also presented are the panel evaluation results obtained by rating the smallest values (determined by inspection) of their basic non-acoustic properties: service life and mechanical resistance, construction, maintenance and replacement costs, and service life costs of noise walls.

It should be noted that the construction cost and the long-term panel efficiency data, as given below, should be considered with a degree of caution because the data on average wall construction costs for individual panel types, taken from [32], were determined in 2010 based on the survey of German, Austrian, Dutch, Italian, and French infrastructure operators and panel manufacturers, and it is therefore quite probable that they somewhat deviate from the market prices currently applicable in the south-eastern European countries. In addition, because as many as 80 % of transport infrastructure operators in the EU countries do not have an officially adopted maintenance program for noise walls [32], the data on the average maintenance and replacement costs and on the average service life costs (for the period of 50 years) were taken from the American literature [24, 33] and adapted to the presentation in SI units. However, as all three cases involve average values determined on a large sample, it was concluded that they represent a satisfactory basis for the economic evaluation and comparison of panels, as conducted in this paper.

4.1. Concrete panels

Concrete panels are composed of two layers: load-bearing layer and absorbing layer. The absorbing layer is made of porous concrete (manufactured using 3-5 mm aggregate grains of, for instance, expanded clay, wooden fibres, or rubber granules) and it usually measures up to 15 cm in thickness. It is installed on the load bearing reinforced-concrete layer of up to 20 cm in thickness. Concrete panels are nowadays the most frequently used panels for the construction of traffic noise walls because of their considerable durability, stability, and resistance (500 to 1000 kg/m^2 and more), the expected service life of at least 40 years, and numerous fastening and shaping possibilities - making them easily adaptable to any kind of environment.

A considerable weight of these panels can be a problem and is likely to increase the cost of transport to greater distances. In addition, because of panel weight, they are not suitable for installation on viaducts and bridges. Special assembly techniques are used during panel installation to reduce the traffic closure time. The usual 4 m distance between wall posts implies lower cost of foundations and overall realisation of these posts, but the total average construction cost, amounting to approximately 225 €/m^2, is higher compared to the cost of walls with metal or wooden panels.

Due to considerable resistance of concrete panels, they are not likely to suffer damage by the impact of skidding vehicles or fragments, by the pressure of snow drift during snow clearing operations, and as a result other occurrences during maintenance activities. Rough surface of concrete panels does not attract graffitists as it requires consumption of greater quantities of paint which is why vandalism is normally not a problem. As concrete panels are highly resistant to extreme temperatures, UV radiation, moisture, ice, and salt, the maintenance aimed at preserving structural and aesthetical integrity of the structure is rarely needed. Nevertheless, some moisture related damage has been registered on the absorbing layer made using wooden fibres in the bottom parts of the structure (1 m above the surface of the terrain). In addition, absorbing layers containing expanded clay may peel because of an impact, and are not resistant to freezing. Yet, the cost of maintenance and replacement of these panels, standing at approximately 40 €/m2, is still the lowest compared to other considered panels. Because of low maintenance costs, average registered life cycle costs stand at approximately 305 €/m2.

Disposal of walls made with concrete panels is relatively simple, as procedures similar to those used for other concrete products are utilised for the demolition of walls and for the recovery/reuse of concrete panels. It is generally considered that the recyclability of these panels stands at as much as 80 %.

4.2. Metal panels

Metal panels are made of (galvanized) steel, stainless steel, or aluminium, and are composed of two lacquered plates 0.5 and 1.0 mm in thickness, between which rock wool 50, 80, or 100 mm in thickness is installed. Service life of steel panels varies from 20 to 25 years, while that of aluminium panels amounts to 30 years. Because of small panel weight, they are mostly installed on bridges and viaducts, on the existing retaining walls of limited carrying capacity, and to increase the height of the existing noise walls. When selecting their location, it is important to consider the fact that high temperatures of the air and soil immediately next to the wall can negatively affect, due to insolation and heating of panels, natural growth of the surrounding vegetation.

Because of small panel weight, the costs of supplying panels to the construction site are quite low. During installation of aluminium panels, care must be taken to prevent direct contact between the aluminium and other metals (steel in particular), because the aluminium's reaction is similar to that of zinc in the galvanisation process, i.e., it behaves as a "sacrificial" element that will disintegrate in a very short period of time. An anticorrosive coating of panels is necessary in the case of high exposure to salt and moisture. In addition, as all metal panels are good conductors, they should not be used near electric power lines unless an appropriate grounding of all metal components can be ensured. Panels are installed simply by means of cranes, and the traffic closure time, if any, during installation of these walls is relatively short. However, realisation of connections necessitates the use of scaffolding the installation of which requires a lot of space, work, and time. The standard 3 m spacing between posts and foundations implies incurrence of greater costs for the realisation of foundations and posts, as compared to the cost of walls with concrete panels. However, an average construction price of this wall type is smaller compared to concrete walls and amounts to approximately 215 €/m^2.

On the other hand, metal panels require more maintenance compared to concrete panels, especially in coastal areas and urban areas. The panels will gradually rust in the case of great quantities of humidity and salt in the air. If the panels are not coated with an anticorrosive paint or if they are not galvanised, the rust will soon pass from the panels to other elements of the wall. If there are no bracings within the panels, warping of panels may occur already at small stress levels as caused by normal changes in temperature. In addition, small resistance of these panels (less than 400 kg/m2) and small thickness of metal plates, make these panels highly susceptible to damage caused by vandalism, impacts by cars or airborne fragments, and as a result maintenance and snow clearing operations. Because of their smooth surface, these panels are often targeted by graffitists. For the above reasons, the cost of maintenance and possible replacement of such panels, standing at approximately 120 €/m^2, is lower only when compared to transparent panels, while average registered service life costs amount to as much as 515 €/m^2.

Metal elements can fully be recycled, but special recovery procedures must be planned for the panel infill made of mineral wool or rock wool.

4.3. Wooden panels

Wooden panels are made either of solid wood, laminated wood, or plywood. Panels with the face of brushwood and the interior of rock wool are also regarded as wooden panels. Wood is considered as an environmentally friendly material highly suitable for the construction of wall panels. Because it blends very well with the environment, this panel type has often been the first choice of landscape architects, although its expected life of 20 or 25 years is very short compared to other panels analysed in this study.

Thanks to their small weight, the cost of delivery of wooden panels to construction site is quite reasonable. Foundations are simple and do not require special procedures such as piling, which is often required in the case of concrete panels when higher walls are built. During installation, wooden panels are inserted between the posts and are then fixed to one another by nails or screws which should be made of corrosion-resistant material (stainless steel or aluminium). The principal advantage of such connection method is that it enables rapid and simple assembly and disassembly of panels, which is why the traffic closing time during construction of such walls is relatively short. The panels are simply installed by means of cranes. However, realisation of connections necessitates the use of scaffolding, the installation of which requires a lot of space, work, and time. Estimated average construction costs of the walls based on wooden panels are the lowest and stand at approximately 205 €/m^2.

Despite the lowest construction price, the use of wooden panels has proven to be problematic in the long run. Although, from the acoustic standpoint, wood exhibits a satisfactory resistance (more than 20 kg/m^2), it is not a structurally strong material and can easily be broken when hit by a vehicle, which causes cracking and reduces its noise protection efficiency. Wooden products are not dimensionally stable, i.e., due to weather influences (sun, moisture) or attacks by insects, wooden panels warp and shrink over time provoking the opening of holes in the panel connection zones, especially if the wood had not been sufficiently dried before the panels were manufactured. The greater the thickness of wooden panels, the greater the warping problem will be during the service life of panels. The use of panels chemically treated to improve their durability, has resulted in a pronounced deterioration over time at connections between panels and posts, because of chemical reaction between their materials. In addition, the impregnation or coating of wooden materials is problematic in the case of fire because of emission of harmful gases into the environment. Although an impregnated wood is used during the manufacturing process, these panels still require periodic application of an appropriate coating, primarily to protect them against moisture and insects, but also because the original paint loses its gloss and becomes paler over time. Every repair or replacement of damaged parts of wooden panels is highly visible, unless conducted by means of elements supplied at the same time as the originally installed elements, and exposed to similar weather influence. Because of the above, the estimated cost of the maintenance and replacement of such panels stand at approximately 115 €/m^2, while an average registered life cycle (service life) cost amounts to 360 €/m^2.

The problem of recyclability is the most acute precisely in the case of wooden panels as their quality at the end of service life is not sufficient for the recovery or recycling because of exposure to weather conditions. The basic problem with the use of wooden panels lies in the use of mineral wool or stone wool in internal layers of the panels and, in recent times, the issue of deforestation and environmental effect of the impregnating substances used to improve durability of wood has also been raised. The removal and disposal of wooden panels could be considered hazardous to the environment precisely because of the need to use various protective coatings. However, despite such treatment, the quality of the wood of these panels will most probably be insufficient for end-of-life recovery. In addition, wooden panels burn just like any other wooden barrier or fence, and the smoke and ashes (arsenic, benzene, chromium, creosol, pentachlorophenol) released to the environment during combustion of the treated wood are considered toxic. For these reasons, the recyclability of such panels is the lowest, and varies from 20 to no more than 40 %.

4.4. Transparent panels

Transparent panels consist of polymethacrylate plates 15 to 25 mm in thickness, placed in a steel frame. These panels enable simultaneous achievement of two goals: they have satisfactory acoustic properties for reducing propagation of traffic noise while, simultaneously, they are an aesthetically pleasing solution for drivers and protected population, and they do not block view of the surrounding area. They are most often recommended for aesthetic improvement of the wall structure, and, because of their small weight, they can readily be installed onto the existing structures. The usual service life of transparent panels ranges from 20 to 25 years. Transparency is the main reason for installation of such panels as, due to their reflectivity, they enable a relatively small reduction of noise at the place of immission. Such panels are exclusively used if the road/railway users or the local population wish to have an undisturbed view of an exquisite scenery, or when the transparency of the wall is required by owners of adjoining commercial facilities for marketing purposes (in such a case they should bear the difference in the price of panels).

Thanks to their small weight, the cost of delivery of transparent panels to construction site is quite low. Panel dimensions (area and thickness) may pose some problems in the transport and installation, especially if the panels of the biggest possible dimensions are used to reduce the costs of foundation work (anchoring). However, big dimensions increase stress values in panels during their installation. That is why installation methods vary to a great extent depending on the material transparent panels are made of (glass, acryl, plexiglass, etc.) and panel dimensions. The basic principle to be used during assembly of such thin panels is to prevent or reduce to minimum the occurrence of stress in the panel as that could provoke panel cracking or, as a result, the panels can fall out of the frame. During installation, it is imperative to respect tolerances relating to the spacing and adhesion of panels, posts, and sealing substances. For instance, if the spacing between panels and posts is too large, the panel will detach during its service life from the post, which can result in excessive movements of panels due to vibrations or wind action. In the case this spacing is insufficient, the sealing substance at the connection, and the panel itself, will not be able to adequately expand with an increase in temperature, which will provoke ununiform stress in the panel and its buckling or cracking. High price of transparent panels and the usual 3 m spacing between posts and foundations, which implies greater costs in the realisation of foundations and posts when compared to concrete panels, ultimately leads to highest installation cost when compared to all other panel materials considered in this study. An estimated average installation costs amount to 320 €/m^2 of these panels.

To keep the panels transparent, they must regularly be cleaned, especially if they are installed at an angle that prevents natural cleaning by rain. The smooth surface of these panels is also attractive to graffitists. The access required for the panel cleaning operations is not problematic from the side of the transport facility, which is more exposed to the accumulation of impurities. The problem usually occurs if the external side of the wall is hardly accessible or altogether inaccessible as, in such cases, the impossibility of maintaining a satisfactory level of panel transparency might greatly affect safe operation of traffic. In addition, some transparent plastic materials are sensitive to UV radiation. If the panels made of such materials are exposed to long-term insolation and are not additionally protected against UV radiation with stabilizing additives or coatings, they will become opaque and will lose colour and will ultimately become partly or even fully non-transparent. In fact, even with protection, the panel will over time become non-transparent. Experience gained by designers and infrastructure operators shows that transparent panels require the highest level of maintenance. Compared to other materials, transparent panels are the most sensitive to impacts due to vandalism, skidding of vehicles, impact of flying fragments, snowdrift pressure resulting from snow clearing operations, and other occurrences during maintenance activities.

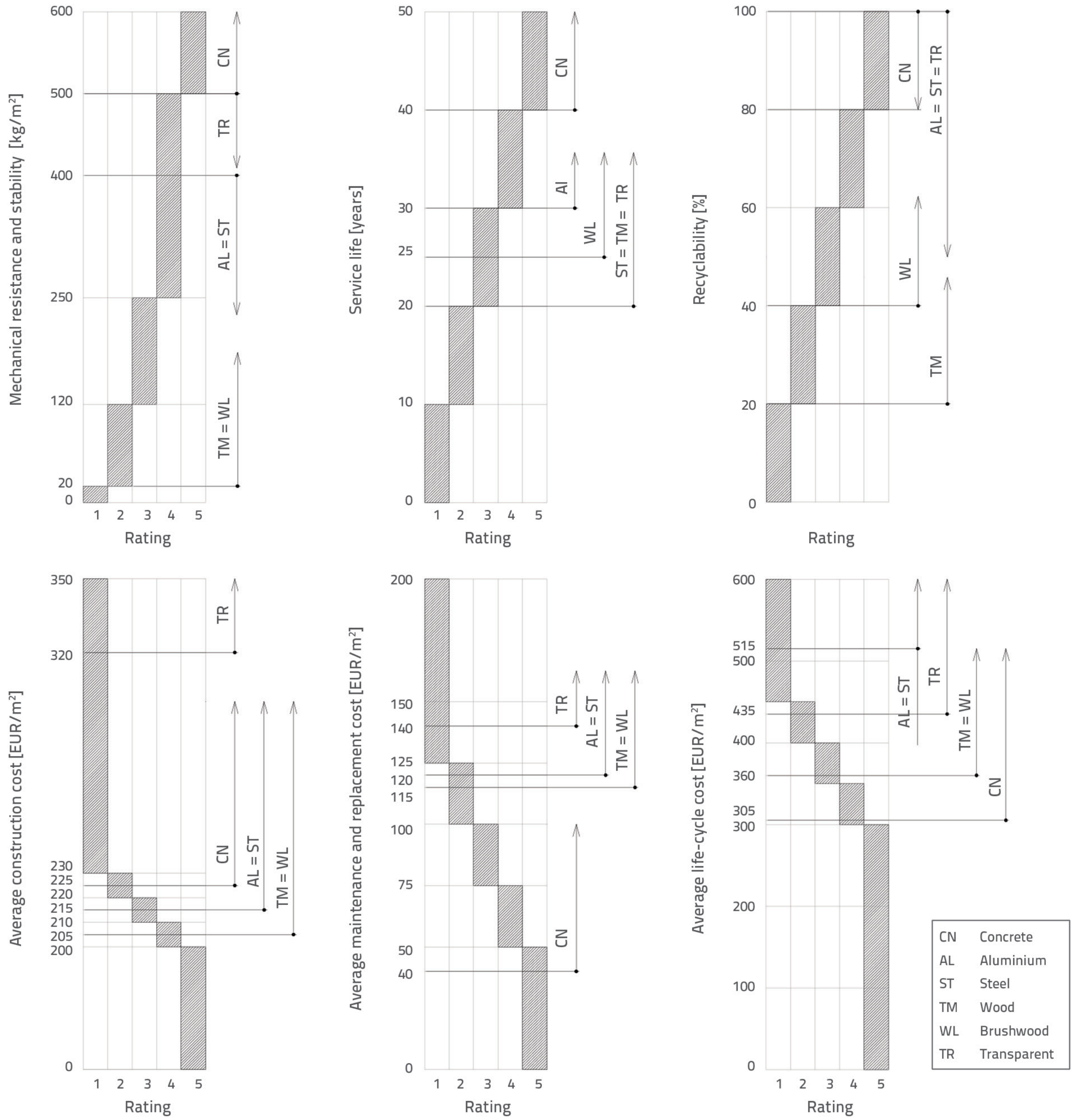

Figure 4. Panel rating according to lowest values of six non-acoustic properties (criteria)

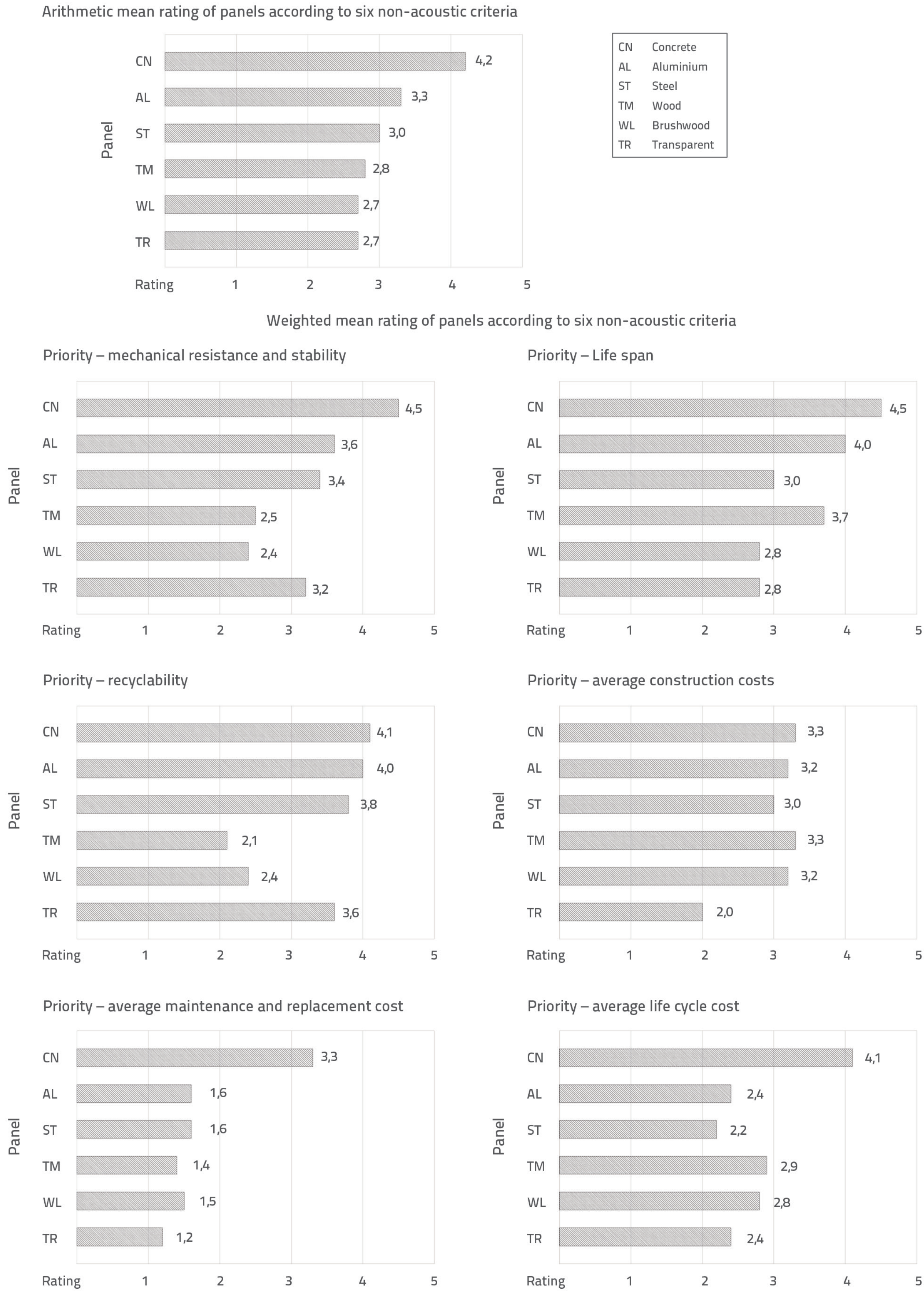

Figure 5. Results obtained by calculating arithmetic and weighted average rating for panels according to six non-acoustic properties (criteria)

Damaged panels cannot be repaired, leaving replacement as the only option. Because of that, estimated average maintenance and replacement costs of transparent panels, amounting to 140 €/m^2, are the highest compared to other materials considered in this study. On the other hand, service life costs estimated at 435 €/m^2, are lower compared to metal panels.

Although transparent panels are almost one hundred percent recyclable, the issue that might appear is who will assume the cost of panel transport to the manufacturer.

4.5. Assessment of panels

The panel assessment was conducted by ranking the lowest registered values of six non-acoustic properties (criteria): the lowest registered service life and mechanical resistance, recyclability, construction, maintenance and replacement costs, and the entire service life cost of panels of these noise walls. These criteria were rated from 1 (worst grade) to 5 (best grade) and then each individual panel type was ranked by each of its properties based on the previously described collected and systematized panel property data (Figure 4).

To determine an average grade according to the priority criteria set by infrastructure operators for the selection of panel materials, six weighted arithmetic mean grades were calculated, in addition to non-weighted arithmetic grades, for each panel type. In this calculation, weight 0.5 was allocated to the priority criterion, while weights amounting to 0.1 were allocated to the remaining criteria considered in the study. Results obtained by calculating average grades (ratings) are presented by means of diagrams shown in Figure 5.

5. Conclusion

The research presented in this paper was motivated by the fact that investments in the development and modernisation of road and rail infrastructure over the oncoming years will require and increased construction of noise walls - which are the most frequent traffic noise protection measure used in Croatia. Although they are still considered as traffic equipment, noise walls require a large quantity of resources and have a considerable effect on the built environment. That is why, when planning and designing noise walls, it would be highly advisable to select those panels that present highest possible levels of durability, safety, and sustainability.

The objective of the research was to lower the level of uncertainty during selection of noise wall panels, and to improve the traffic noise management process in Croatia. Properties of panels made of four basic material types (concrete, metal, wood, and transparent polymethacrylate) were studied under assumption that basic acoustic properties for wall structure had been fully met. Thus, the research could focus on six non-acoustic properties (criteria) of panels that must be considered by engineers.

The systematisation and assessment of the data collected from secondary sources has revealed that concrete panels have the highest ranking as to their mechanical resistance and stability, service life, and maintenance costs. Metal and transparent panels are highly recyclable, but their average service life costs are high. Although construction costs of wooden panels are quite low, their other non-acoustic properties are much worse compared to concrete, metal, and transparent panels.

The multicriteria analysis revealed that concrete panels have the highest average ranking according to non-acoustic properties considered in the study. As the price is often the most important criterion for the selection of panel material, the results obtained by calculating the weighted average cost of wall construction regarding the panel material type, are particularly interesting. These calculations show that, despite a higher purchase price of panels, concrete panels are as economical as metal or wooden panels. If the emphasis is shifted from the construction price to the long-term sustainability of panels considered through maintenance and replacement costs, concrete panels still have a significant advantage due to their high resistance and durability. Excellent behaviour of wall structures with concrete panels, and their good recyclability, have resulted in the highest weighted ranking regarding life-cycle costs.

The results obtained in this research show that, when selecting the panel type during design of new noise walls, especially in rural areas, an advantage should be given to concrete panels, and then to metal panels (in situations of lower exposure to weather influences and for use on structures), while the use of wooden and transparent panels should be limited to highly valued scenic areas only.

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