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Impact of vertical traffic calming devices on environmental noise

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Research Paper

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Impact of vertical traffic calming devices on environmental noise

Increasing numbers of people living in urban areas are being exposed to harmful action of environmental noise, which severely affects their health and quality of life. The predominant source of environmental noise in such areas is road traffic, and a frequently used measure to curb down this noise involves reduction of driving speed. The influence of vertical traffic calming devices, normally used to improve traffic safety, on the degree of noise reduction, is analysed in this study. The analysis was carried out on seven urban two-lane two-way roads, on which various types of speed bumps and speed humps are installed.

Key words:
traffic calming devices, speed bumps, speed humps, noise protection, road traffic

Prethodno priopćenje

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Utjecaj opreme za smirivanje prometa na razine buke u okolišu

Sve veći broj stanovnika u urbanim sredinama izložen je štetnom djelovanju buke okoliša, koja u značajnoj mjeri narušava njihovo zdravlje i kvalitetu života. Dominantan izvor buke okoliša u takvim područjima je cestovni promet, a jedna od učestalo primjenjivanih mjera za smanjenje razina buke je smanjenje brzine vožnje. U radu je analizirano kako oprema za smirivanje prometa, koja se uobičajeno primjenjuje radi povećanja sigurnosti prometa, utječe na smanjenje razina buke. Analiza je provedena na sedam dvotračnih dvosmjernih gradskih cestovnih prometnica na kojima su ugrađeni različiti tipovi umjetnih izbočina i uzdignutih ploha.

Ključne riječi:
oprema za smirivanje prometa, umjetne izbočine, uzdignute plohe, zaštita od buke, cestovni promet

Vorherige Mitteilung

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Einfluss verkehrsberuhigender Vorrichtungen auf den Umgebungslärmpegel

Immer mehr Einwohner in städtischen Gebieten sind den schädlichen Auswirkungen von Umgebungslärm ausgesetzt, die ihre Gesundheit und Lebensqualität erheblich beeinträchtigen. Die Hauptquelle für Umgebungslärm in solchen Gebieten ist der Straßenverkehr, und eine der häufig angewendeten Maßnahmen zur Senkung des Geräuschpegels ist die Reduzierung der Fahrgeschwindigkeit. Die Arbeit analysiert, wie sich verkehrsberuhigende Vorrichtungen, die üblicherweise zur Erhöhung der Verkehrssicherheit eingesetzt werden, auf die Senkung des Geräuschpegels auswirken. Die Analyse wurde auf sieben zweispurigen Zwei-Wege-Stadtstraßen durchgeführt, auf denen verschiedene Arten von künstlichen Vorsprüngen und erhöhten Oberflächen installiert wurden.

Schlüsselwörter:
Verkehrsberuhigungsmittel, künstliche Vorsprünge, erhöhte Oberflächen, Lärmschutz, Straßenverkehr

1. Introduction

Excessive noise levels have become an increasingly disturbing problem in the present-day world [1]. Due to rapid urbanisation process, because of which more than half of the world's population and more than three quarters of the EU population currently live in cities, an increasing number of people are exposed to environmental noise pollution [2]. A predominant source of environmental noise in urban areas is undoubtedly the road traffic – which is a traffic mode that affects the people`s health and quality of life much more than the railway traffic and air traffic combined [3]. Numerous studies have shown that road traffic noise negatively affects cognitive abilities of humans as well as their mental and physical health, thus causing hormonal disorders, diabetes, and cardiovascular diseases [4-8]. High noise levels in the evening and at night are a particular problem, because they interfere with the rest and sleep of people and consequently prevent normal functioning of human body during the daytime [9].
Measures commonly used to reduce road traffic noise levels in urban areas are: construction of silent driving surfaces, development of more silent vehicles and tyres, and traffic management (driving speed reduction, ensuring free traffic flow at night, redirecting certain percentage of traffic to other roads in the city, ban on motor vehicle traffic in city centres, and encouragement of more passive driving practices) [10]. The driving speed reduction can be accomplished with traffic-technical and construction measures. The first ones relate mostly to speed limitation and control, and the latter to the choice of cross-section elements, and use of vertical traffic calming devices [11]. The aim of this research is to analyse the influence of vertical traffic calming devices, speed bumps and speed humps in particular, on the reduction of road traffic noise levels in urban areas.

2. Regulations and overview of previous studies

The Croatian regulation regarding the use of vertical traffic calming devices is outlined below, and an overview is given of previous studies focusing on the influence of speed bumps and speed humps on the traffic safety and noise abatement situation in urban areas.

2.1 Regulations

According to Croatian *Traffic Signs, Signalisation and Road Equipment Regulation* [12], the term traffic calming devices and measures includes all physical, light-emitting and other devices and obstacles that influence vehicle speed reduction on critical parts of a roadway. They are not only used for driving speed reduction, but also to reduce the number and consequences of traffic accidents, to change driving habits, and to prevent environmental pollution.

Regarding the operating mode, traffic calming devices and measures imposed by the Regulation [12] can be divided into the following three groups:

- Physical obstacles (forced speed reduction): speed bumps, speed humps;
- Warning equipment (visual, acoustic, vibrating): optical white warning lines, radars with a vehicle speed indicator, acoustic warning lanes, vibrating lanes;
- Traffic management equipment (passage banning and vehicle directing equipment): passage banning and vehicle directing posts.

Speed bumps and speed humps are usually installed on local and unclassified roads, next to public buildings and areas (schools, kindergartens, playgrounds, etc.) where the vehicle speed reduction is necessary for the traffic safety, based on a traffic report and the feasibility analysis [13], with the prior consent pursuant to Article 44 of the Law on Public Roads [14]. The application of these measures is not allowed on roads and streets frequently used by ambulance vehicles (e.g. hospital driveways).
They have to be marked with appropriate traffic signs and pavement markings, and their surfaces have to be made of anti-skid materials and marked with permanent retro-reflective materials on the side from which the vehicle is approaching. They have to be properly anchored into the asphalt pavement so as to prevent detachment of individual elements or their parts during passage of vehicles. They must not have any edges in the direction transverse to the driving direction, at the connection with the pavement.
Speed bumps are ready-made modular products. They are made of rubber or plastics but can also be made of asphalt for speeds lower than 30 km/h. The bumps are convex in profile, and are positioned before a traffic calming zone, across the half or the entire width of a traffic lane, mostly in residential zones (Figure 1). Their colour must differ from that of the roadway surface so that they can easily be spotted during the day and night, and they must be marked with direction lines H55 or H55-2. If they are installed in a series, they have to be 20 to 60 m apart, depending on the situation. Limit dimensions of speed bumps are defined according to speed limit, as follows:

- $V_{all} \leq 50$ km/h: width min. 60 cm, height max. 3 cm
- $V_{all} \leq 40$ km/h: width min. 90 cm, height max. 5 cm
- $V_{all} \leq 30$ km/h: width min. 120 cm, height max. 7 cm.

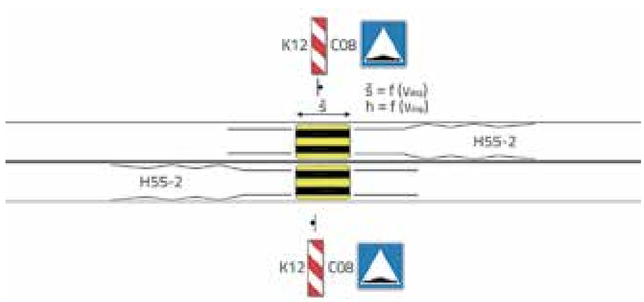

Figure 1. Speed bumps according to [12]

Speed humps are constructed surfaces with a trapezoidal profile for a forced speed reduction. They are installed either individually or in a series, usually in front of marked pedestrian crossings in residential areas (Figure 2). They have to have a different colour from the roadway surface in order to be easily visible, day and night, and they have to be marked with direction lines H55-1 or H55-3. The speed hump height is 7.5 cm, the access ramp gradient is 1:15 to 1:20, and the access ramp length is 100 cm.

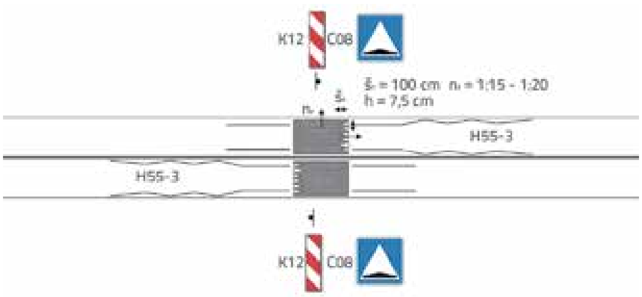

Figure 2. Speed humps according to [12]

2.1. Previous studies

Numerous studies have shown that the use of physical obstacles (speed bumps and speed humps) at critical locations within residential areas significantly decreases the vehicle speed and, according to that, the number and the consequences of traffic accidents are substantially reduced, especially those that include pedestrians involved in accidents while crossing a pedestrian crossing [15-16]. It is outlined in study [17] that the highest number of traffic accidents with lethal outcomes for pedestrians happen at speeds ranging between 30 and 50 km/h, which are typical for urban neighbourhoods. Physical-obstacle parameters that mostly influence reduction in vehicle speed are the ramp length and ramp height: the longer the ramp, the lower the speed across the obstacle [18]; an increase in obstacle height by 1 cm leads to speed reduction of 1 km/h [19]. In addition, it is very important that the obstacle is made of appropriate materials so as to avoid skidding, the obstacle must be produced with minimum deviations from prescribed dimensions, it must be properly marked with adequate signs and markings, it should be installed at an appropriate distance from road intersections and pedestrian crossings, and it must be visible from a sufficient distance (a required sight distance to the obstacle must be ensured) [20].

However, the use of physical obstacles has its deficiencies: they create difficulties for snow removal from roadway during winter months; they slow down ambulances and fire fighting vehicles (by up to 10 s per obstacle); they are dangerous for motorcyclists who, during a fall from the motorcycle, may suffer major bodily injuries even at relatively low driving speeds; ruts and potholes are created immediately before and after such obstacles, which increases the pavement maintenance costs; the design of an obstacle that would result in the same speed reduction and the same comfort level for all vehicles is impossible (the crossing is extremely uncomfortable for trucks and buses, even at extremely low driving speeds while, for example, such a crossing is hardly felt while driving a Sedan or a four-wheel drive SUV); drivers of passenger vehicles often avoid crossing physical obstacles for comfort reasons (they go around them using additional lane for public transport vehicles, bus stations, etc., they pass between two obstacles in adjacent traffic lanes, and they use alternative routes, i.e. surrounding streets in which, consequently, the traffic volume increases and the traffic safety decreases); old vehicles and low chassis vehicles incur damage when crossing the obstacles even at low driving speeds; fuel consumption and emission of harmful gasses increases due to deceleration and acceleration prior to and after the obstacle (CO content increases by approximately 60 %, HC by approximately 50 %, and CO_2 by approximately 25 %); they are often constructed illegally, without local government permits (a defective construction can lead to vehicle damage and reduced traffic safety) [20-25].

The results of previous studies, in which the impact of physical obstacles on the current noise situation in urban areas is analysed, show that noise levels in obstacle-containing areas can be either lowered, increased, or stay unchanged. Parameters that influence the previously mentioned are the following: obstacle type, adequacy of construction, choice of location at which obstacle is installed, traffic flow structure, driver behaviour, and the way in which traffic signalisation is installed [26].

It is mentioned in [27] that the driving speed reduction by 30 km/h in the physical obstacle area almost always results in a noise level decrease. A study conducted in Great Britain [28] has revealed the following: if passenger vehicle drivers at the location of two consecutive obstacles reduce their driving speed by 16 km/h on an average, the noise levels at the obstacles decrease by 8.2 dB(A), and between them by 3.9 dB(A); if the driving speed is approximately 20 km/h, passenger vehicle noise levels at the location of the obstacles decrease by 10 dB(A), while the noise levels of buses and light-duty (delivery) vehicles increase by 4 dB(A) or 8 dB(A). In their study [29], the authors measured noise levels of passenger vehicles shortly before and after installation of two consecutive obstacles (50 m apart from each other). They concluded that noise levels at the location of the obstacles decreased by 3 dB(A), and on the segment between them by 1 dB(A).

Aggressive and fast driving, resulting in hard impact on a physical obstacle, and in abrupt deceleration in zones before and after the obstacle, is the most common cause of passenger-vehicle noise level increase at such locations [30-33]. Nevertheless, noise levels increase the most at 20 m after the obstacle [34]. It is mentioned in studies [23-25, 30] that obstacle crossing by buses and trucks results in higher increase in noise levels, compared to passenger vehicles. The authors of the study [35] point out that noise levels of passenger vehicles at lower driving speeds are generally lower than the noise levels of trucks and buses operating at the same speed. The reason for that is the fact that in the case of such bigger vehicles the rolling noise (noise resulting from the friction between vehicle tyre and roadway surface) is not dominant at lower speed, i.e. the dominant noise is that of the engine and exhaust system.

Furthermore, research results obtained by analysing impact of obstacle geometry on noise showed the following: while crossing a speed hump of trapezoidal profile, trucks and buses generated higher noise levels than when crossing a speed hump of sinusoidal profile. In the case of passenger vehicles, no such significant difference in noise was noted when crossing obstacles with different profiles [36]; the driving speed and noise levels reduce with the length of physical obstacle [22]. And, finally, it is described in [37] how humans perceive decrease in road traffic noise levels: noise decrease of up to 1 dB(A) is not even noticed by human ear; 3 dB(A) decrease in noise is noticed; 6 dB(A) noise decrease is considerably noticed; 10 dB(A) noise reduction is felt by humans as if the noise level decreased twofold.

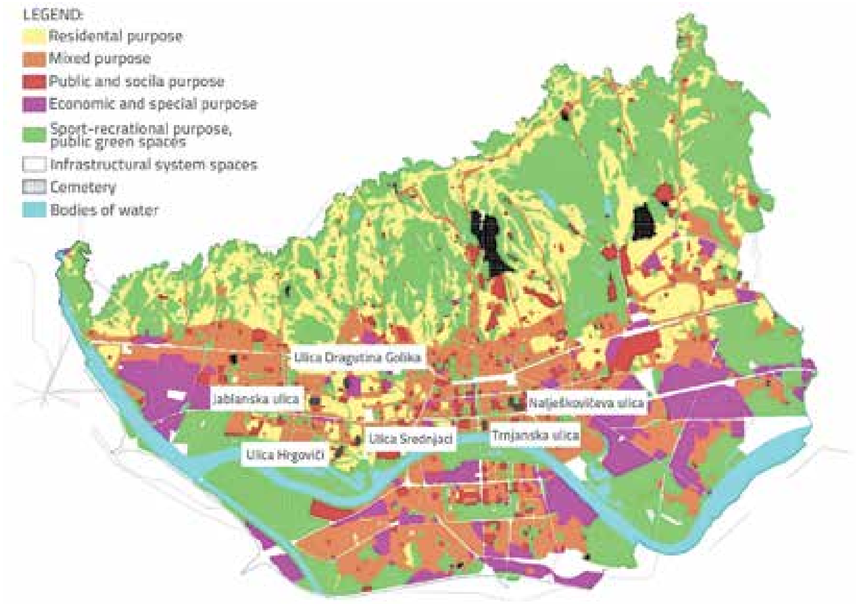

Figure 3. Locations at which testing was conducted [40]

3. Description of testing

The testing was conducted in the city of Zagreb at seven roads on which various types of traffic calming bumps and humps are installed (Table 1). The following location selection criteria were applied:
- The chosen road is a two-lane, two-way road;
- The longitudinal gradient of the chosen road is lower than 1 % (negligible);
- The observed segment of the chosen road is straight in a horizontal sense, and is situated no less than 50 m away from road intersections.

Mixed-occupancy mostly residential buildings are situated at the locations under study (Figure 3). According to Croatian *Regulation on the highest allowed noise levels in working and residential areas* [38], noise levels along the road must not be higher than 65 dB(A) during the periods "day" and "evening", and 50 dB(A) during the period "night". The duration of the day, evening and night periods is regulated by the *Noise Protection Act* [39]: the period "day" lasts from 7 a.m. to 7 p.m., the period "evening" lasts from 7 p.m. to 11 p.m., and the period "night" lasts from 11 p.m. to 7 a.m. The highest allowed planned noise levels regulated by the *Urban Master Plan* (GUP) of the City of Zagreb [40] depend on the occupancy of the area, and are therefore often not identical even on different segments of the same city road. At the locations considered in this research, noise levels are dissimilar and are in most cases lower than the ones specified in the Regulation (Table 2).

Table 2. Highest allowed planned noise levels regulated by GUP of the City of Zagreb [40]

Location code	L_{Aeq} (dB(A))	
	periods "day" and "evening"	period "night"
L1	55	45
L2	50	50
L3	50	50
L4	50	50
L5	65	50
L6	50	50
L7	50	50

Short noise level measurements were conducted for a duration of 15 min at every studied location. They were carried out during the

Table 1. Locations at which testing was conducted

Location code	Street	City district	Type of traffic calming device
L1	Dragutina Golika Street	Trešnjevka – North	trapezoidal rubber speed hump
L2	Jablanska Street	Trešnjevka – North	transverse concrete speed bump
L3	Hrgovići Street	Trešnjevka – South	spheroidal elliptical rubber speed bump
L4	Srednjaci Street	Trešnjevka – South	transverse cubic speed bump
L5	Trnjanska Street	Trnje	transverse rubber speed bump
L6	Nalješkovićeva Street	Trnje	spheroidal elliptical concrete speed bump
L7	Pile IV. Street	Trnje	narrow transverse concrete speed bump

periods "day" and "night" by applying two Brüel & Kjær sound level meters/analysers, Type 2260 and Type 2270, installed at a 2.0 m horizontal distance from the axis of the closer road lane, and at 1.2 m above the ground surface. The measurements were not carried out during the period "evening" because the impact of traffic calming devices on noise level values had to be tested in the periods of the highest and lowest traffic volume, i.e. in the day and night periods. During all measurements, weather conditions were favourable: air temperature 6°C - 10°C, wind velocity 2 m/s - 3 m/s, air humidity 50 % - 63 %, and air pressure 1007 hPa - 1010 hPa.
In order to test impact of traffic calming devices on the road traffic noise level values, the Sound Level Meters were installed as follows (Figure 4):

- One Sound Level Meter at the cross-section within which the speed bump or speed hump is situated (Measuring Point MM1);
- The second Sound Level meter at the cross-section situated 50 m before or 50 m after the speed bump or speed hump (Measuring Point MM2).

Simultaneously with the noise level measurements, traffic recording was carried out using two GoPro cameras installed near the Sound Level Meters in the areas of the MM1 and MM2 Measuring Points (Figure 4). The time needed by each vehicle to pass through these cross-sections was noted by hand on paper, and each vehicle was placed into one of the following four groups: passenger vehicles, vans, light delivery trucks, buses. The driving speed of the mentioned vehicles was not measured with measuring devices, but only a subjective assessment was carried out by the persons who measured the noise and traffic. It was also noted whether the vehicles decelerated "significantly", "little" or "very slightly" while crossing the traffic calming devices.

Figure 4. Sound Level Meters and cameras at cross-sections in which traffic calming devices are located

3.1. Dragutina Golika Street (L1)

At the street of Dragutina Golika, the research was conducted on the segment between the Vinkovačka and Županijska streets, where trapezoidal rubber speed humps measuring 302.4 cm x 193.6 cm x 6.8 cm, marked by a cylinder-shaped K05 plate, are located (Figure 5). This street segment is mostly used by passenger vehicles, vans and light delivery trucks, as well as city buses. The speed limit in this street is 40 km/h.

Figure 5. Segment under study at Street Dragutina Golika and trapezoidal rubber speed humps [41]

3.2. Jablanska Street (L2)

At Jablanska street, the research was conducted along the segment between Jablanska Odvojak 1 and Rudeška streets, where a transverse concrete speed bump measuring 868.5 cm x 132.9 cm x 3.8 cm, marked by a cylinder-shaped K05 plate, is located (Figure 6). The mentioned street segment is mostly used by passenger vehicles, vans and light delivery trucks, as well as city buses. The speed limit in this street is 40 km/h.

Figure 6. Segment under study at Jablanska street and transverse concrete speed bump [41]

3.3. Hrgovići Street (L3)

At the street of Hrgovići, the research was conducted at the segment between Bartolići and Bernarda Vukasa streets, where spheroidal elliptical rubber speed bumps measuring 299.7 cm x 209.0 cm x 8.3 cm, marked by a K12-3 plate and a C08 traffic sign, are located (Figure 7). The mentioned street segment is mostly used by passenger cars. The speed limit in this street is 50 km/h.

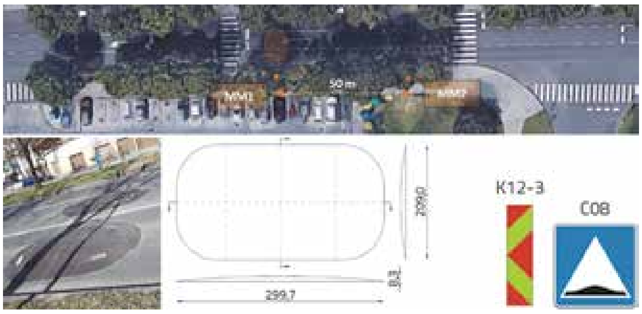

Figure 7. Segment under study in Street Hrgovići and spheroidal elliptical rubber speed bumps [41]

3.4. Srednjaci Street (L4)

At Srednjaci Street, the research was conducted at the segment between Majstora Radovana and Horvaćanska streets, where a transverse cubic speed bump measuring 749.0 cm x 403.1 cm x 8.8 cm, marked by a K12-3 plate and a C08 traffic sign, is located (Figure 8). The mentioned street segment is mostly used by passenger vehicles. The speed limit in this street is 40 km/h.

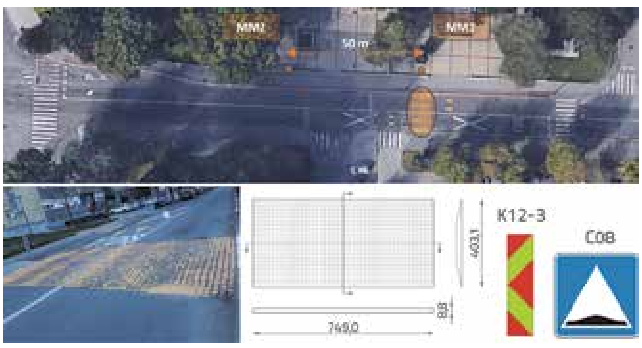

Image 8. The observed segment in Srednjaci Street and the transverse cubic speed bump [41]

3.5. Trnjanska Street (L5)

At Trnjanska Street, the research was conducted at the segment between Prudi IV. and Street Prudi streets, where a transverse rubber speed bump measuring 603.9 cm x 197.7 cm x 8.8 cm, marked by a K12-3 plate and a C08 traffic sign, is located (Figure 9). The mentioned street segment is mostly used by passenger vehicles. The speed limit in this street is 50 km/h.

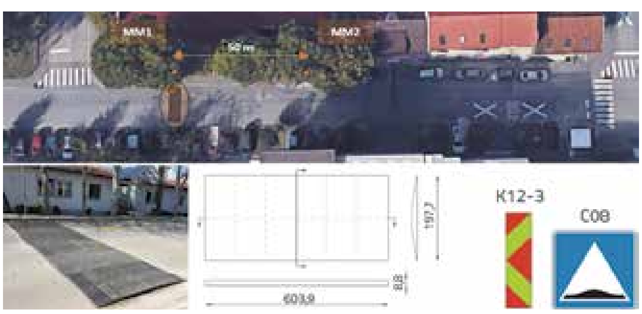

Figure 9. Segment under study at Trnjanska street and transverse rubber speed bump [41]

3.6. Nalješkovićeva Street (L6)

At Nalješkovićeva Street, the research was conducted at the segment between Pile IV. and Zlatarićev prilaz streets, where spheroidal elliptical concrete speed bumps measuring 316.8 cm x 192.8 cm x 11.4 cm, marked by a K12-3 plate and a C08 traffic sign, are located (Figure 10). The mentioned street segment is mostly used by passenger vehicles. The speed limit in this street is 40 km/h.

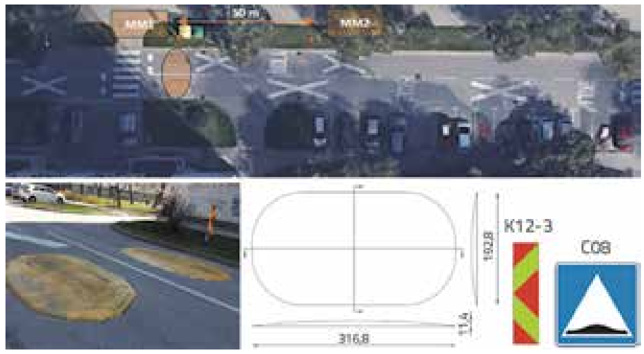

Figure 10. Segment under study at Nalješkovićeva street and spheroidal elliptical concrete speed bumps [41]

3.7. Pile IV. Street (L7)

At Pile IV. Street, the research was conducted at the segment between Cvijete Zuzorić and Nalješkovićeva streets, where a narrow transverse concrete speed bump measuring 607.3cm x 98.7cm x 3.7cm, marked by a K05 plate, is located (Figure 11). The mentioned street segment is mostly used by passenger cars. The speed limit in this street is 40 km/h.

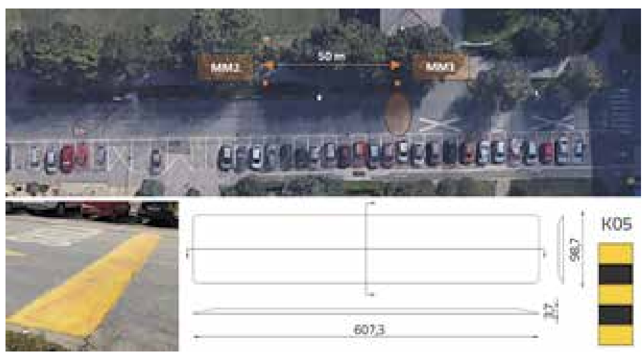

Figure 11. Segment under study at Street Pile IV. and narrow transverse concrete speed bump [41]

4. Test results

The noise measurement results were analysed by specialised computer program Brüel & Kjær Evaluator Type 7820. The following was registered during the analysis (Table 3):

- Maximum noise levels (L_{AFmax}) for ten or less individual vehicles belonging to a particular group (passenger vehicles, vans and light delivery trucks, buses) which successively passed through the observed cross-sections using the closer road

Table 3. Number of vehicles by group obtained during noise measurements for individual and all vehicles

Location code	Number of vehicles															
	period "day"								period "night"							
	OA[a]		KV[b]		LTV[c]		A[d]		OA[a]		KV[b]		LTV[c]		A[d]	
	P[e]	S[f]	P[e]	S[f]	P[e]	S[f]	P[e]	S[f]	P[e]	S[f]	P[e]	S[f]	P[e]	S[f]	P[e]	S[f]
L1	10	133	10	12	4		4		10	51	0[g]		0[g]		2	
L2	10	103	5		4		0[g]		8		0[g]		0[g]		0[g]	
L3	10	73	0[g]		0[g]		0[g]		0[g]		0[g]		0[g]		0[g]	
L4	10	81	0[g]		0[g]		0[g]		6		0[g]		0[g]		0[g]	
L5	10	47	0[g]		0[g]		0[g]		6		0[g]		0[g]		0[g]	
L6	10	36	0[g]		0[g]		0[g]		0[g]		0[g]		0[g]		0[g]	
L7	10	37	0[g]		0[g]		0[g]		0[g]		0[g]		0[g]		0[g]	

[a] – passenger vehicle, [b] – vans, [c] – light delivery trucks, [d] – buses, [e] – noise measurement of individual vehicles, [f] – noise measurement of all vehicles, [g] – left out from further analysis

lane (at the spot of the traffic calming device as well as 50m before or after the device) in the periods "day" and "night";
- Equivalents Noise Levels ($L_{Aeq,15}$) of all vehicles which passed through the observed cross-sections using the closer road lane in 15-minute time periods (at the spot of the traffic calming device as well as 50m before or after the device) in the periods "day" and "night".

It should be noted that at some locations not all vehicle groups were represented at the time of the measurements, and that at some locations in the period "night" no vehicle actually passed during the 15-minute periods. Such measurements were therefore left out from further analysis (Table 3).

4.1. Noise levels for individual vehicles

Diagrams given in Figure 12 show noise measurement results for individual vehicles (L_{AFmax}) at location L1, in the cross-section in which the trapezoid rubber speed hump (MM1) in located as well as in the cross-section located 50 m after that hump (MM2). It was noted during the measurement that most vehicles, while crossing this speed hump type, did not reduce their driving speed significantly, and

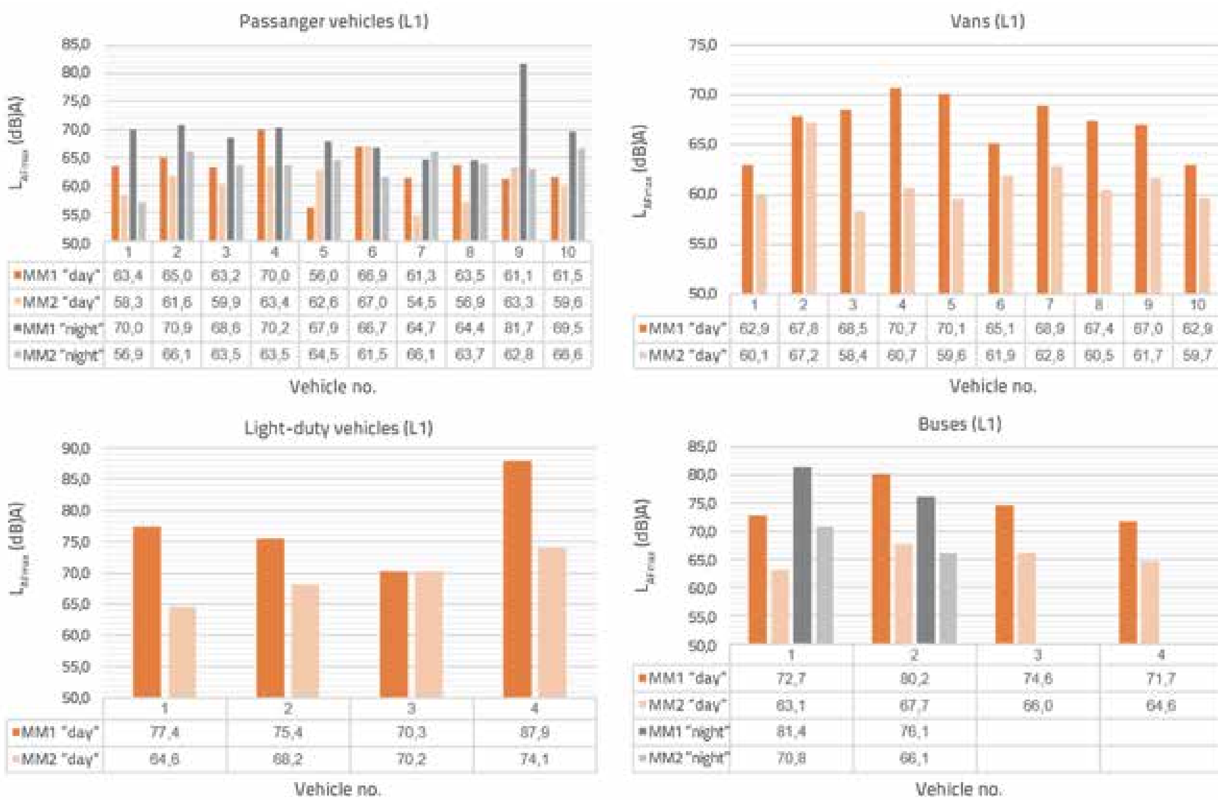

Figure 12. Noise measurement results for individual vehicles at location L1

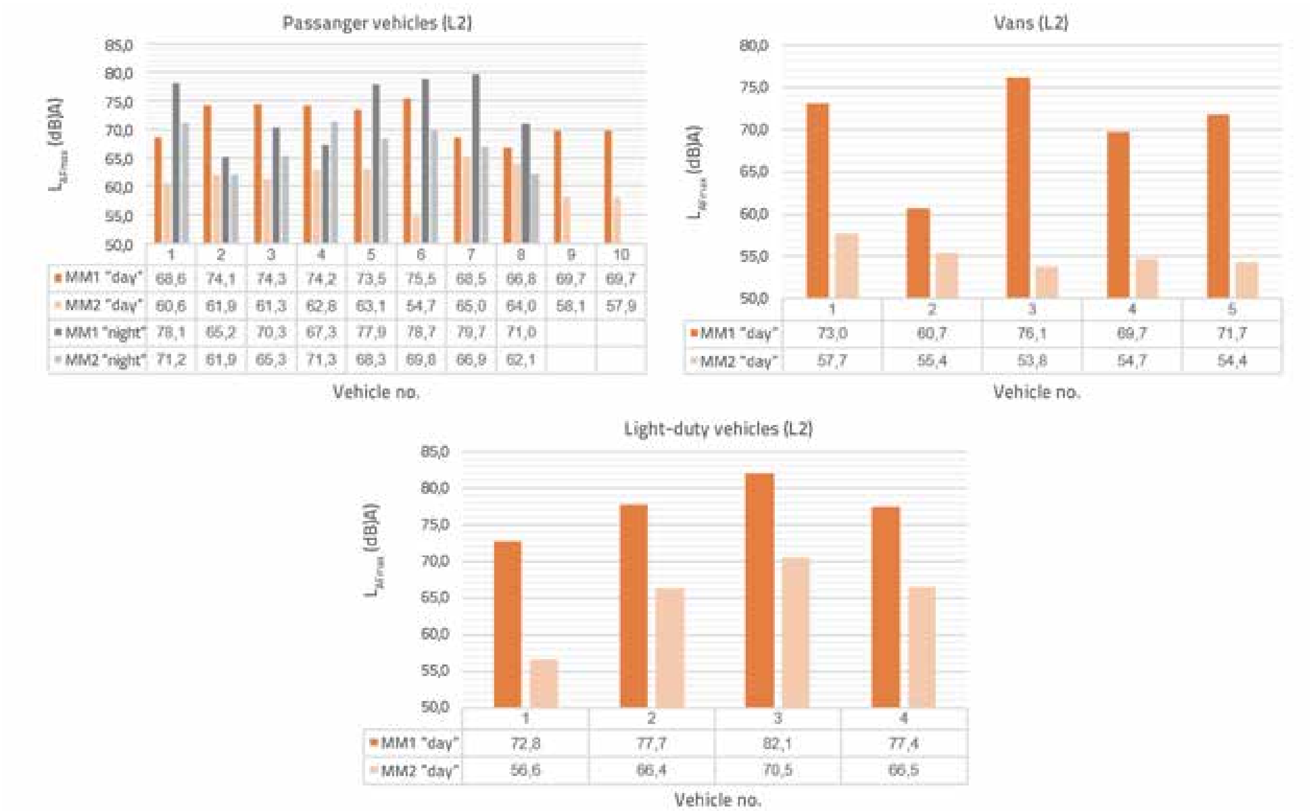

Figure 13. Noise measurement results for individual vehicles at location L2

therefore the hump crossing at high speed (impact) resulted in higher noise levels than the ones on a segment without any traffic calming devices. Exceptions to the mentioned were passenger vehicles nos. 5 and 9 in the period "day" and the passenger vehicle no. 7 in the period "night", which significantly decelerated while crossing the speed hump and therefore generated lower noise levels compared to the observed segment without any traffic calming devices.

Diagrams given in Figure 13 show noise measurement results for individual vehicles (L_{AFmax}) at location L2, in the cross-section in which the transverse concrete speed bump (MM1) is located as well as in the cross-section located 50 m before that bump (MM2). At this location, it was also noted that most vehicles did not significantly reduce their driving speed while crossing the observed speed bump. Consequently, the crossing of the speed bump at high speed resulted in higher noise levels than the ones on a segment without any traffic calming devices. The exception to this was the passenger vehicle no. 4 in the period "night", which significantly decelerated while crossing the speed bump, and therefore generated lower noise levels than in the observed segment without any traffic calming devices.

The diagram given in Figure 14 shows noise measurement results for individual vehicles (L_{AFmax}) at location L3, in the cross-section in which the spheroidal elliptical rubber speed bump (MM1) is located as well as in the cross-section located 50 m after this bump (MM2). The graphics show that no vehicles significantly reduced their driving speed while passing across the speed bump, and therefore generated higher noise levels than at the observed cross-section without any traffic calming devices.

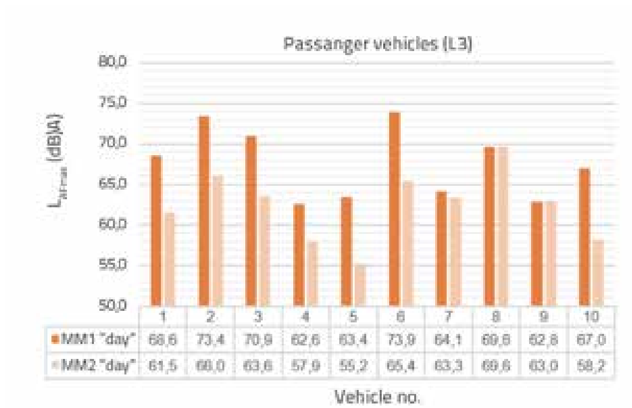

Figure 14. Noise measurement results for individual vehicles at location L3

The diagram given in Figure 16 shows noise measurement results for individual vehicles (L_{AFmax}) at location L5, in the cross-section in which the transverse rubber speed bump (MM1) is located as well as in the cross-section located 50 m after the bump (MM2). During noise measurements at this location, it was noted that all vehicles significantly reduced their driving speed while crossing the mentioned speed bump during the period "day", and therefore the crossing of the speed bump resulted in lower noise levels than the ones on the segment without any traffic calming devices. The opposite happened during the period "night" when all vehicles passed over the speed bump at high speed (mostly cabs), and therefore generated higher noise levels at that cross-section than in the observed cross-section without any traffic calming devices.

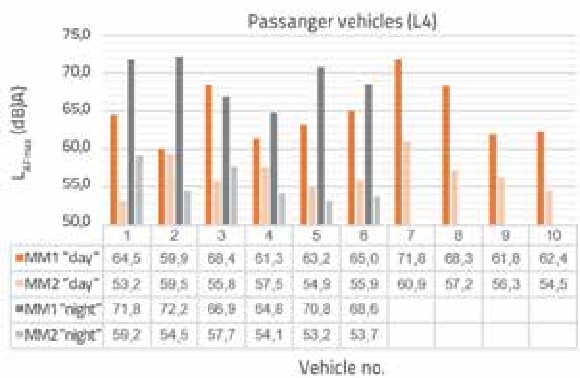

Figure 15. Noise measurement results for individual vehicles at location L4

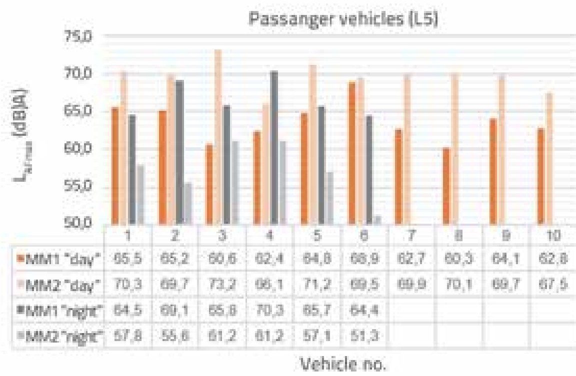

Figure 16. Noise measurement results for individual vehicles at location L5

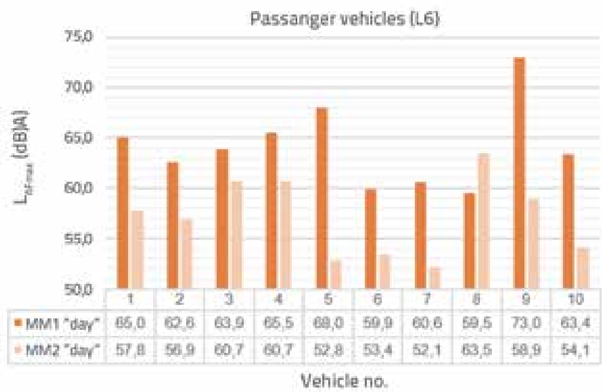

Figure 17. Noise measurement results of individual vehicles at the location L6

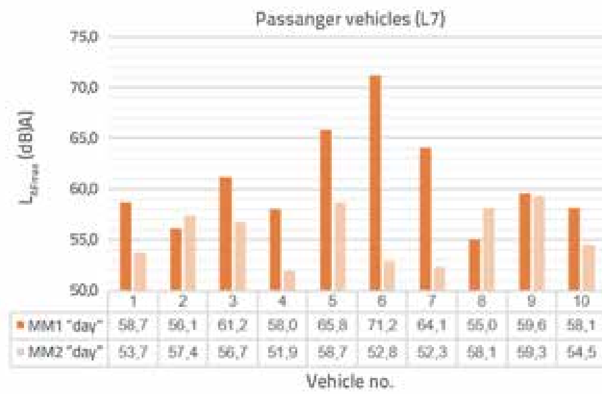

Figure 18. Noise measurement results for individual vehicles at location L7

The diagram given in Figure 17 shows noise measurement results for individual vehicles (L_{AFmax}) at location L6, in the cross-section in which the spheroidal elliptical concrete speed bump (MM1) is located as well as in the cross-section located 50 m before the bump (MM2). At this location, it was noted that most vehicles did not significantly reduce their driving speed while crossing the observed speed bump. According to the mentioned, the crossing of the speed bump at high speed resulted in increased noise levels compared to the ones on the segment without any traffic calming devices. The exception from the mentioned is the passenger vehicle no. 8, which significantly decelerated while crossing the speed bump, and therefore generated lower noise levels in the cross-section compared to those registered at the observed cross-section without any traffic calming devices.

The diagram given in Figure 18 shows noise measurement results for individual vehicles (L_{AFmax}) at location L7, in the cross-section in which the narrow transverse concrete speed bump (MM1) is located as well as in the cross-section located 50 m before the bump (MM2). It was observed during the measurements that most vehicles did not significantly reduce their driving speed while crossing this type of speed bump, and according to that, the crossing of the bump at high speed (impact) resulted in higher noise levels than the ones on the segment without any traffic calming devices. Exceptions from the mentioned are passenger vehicles no. 2 and 8, which significantly decelerated while crossing the speed bump, and therefore generated lower noise levels in that cross section compared to those registered in the observed cross-section without any traffic calming devices.

The diagram given in Figure 19 shows average noise levels of 10 or less successively passing individual vehicles of a specific group ($\overline{L_p}$), which, at a certain location, passed through the observed cross-sections (at the spot of the traffic calming device and 50 m before or after the device) on the closer road lane in the periods "day" and "night". These average noise levels were determined by applying expression (1) [42].

$$\overline{L_p} = 10 \cdot \log \cdot \frac{1}{n}\left(\sum_{i=1}^{n} 10^{L_p/10} \right) \tag{1}$$

where:

$\overline{L_p}$ - average sound pressure level (dB(A))

n - number of successively passing vehicles of a particular group (-)

L_p - sound pressure level in the receptor (dB(A)).

As shown in diagrams given in Figure 19, the locations relevant for the definition of vehicle groups that generated the highest or

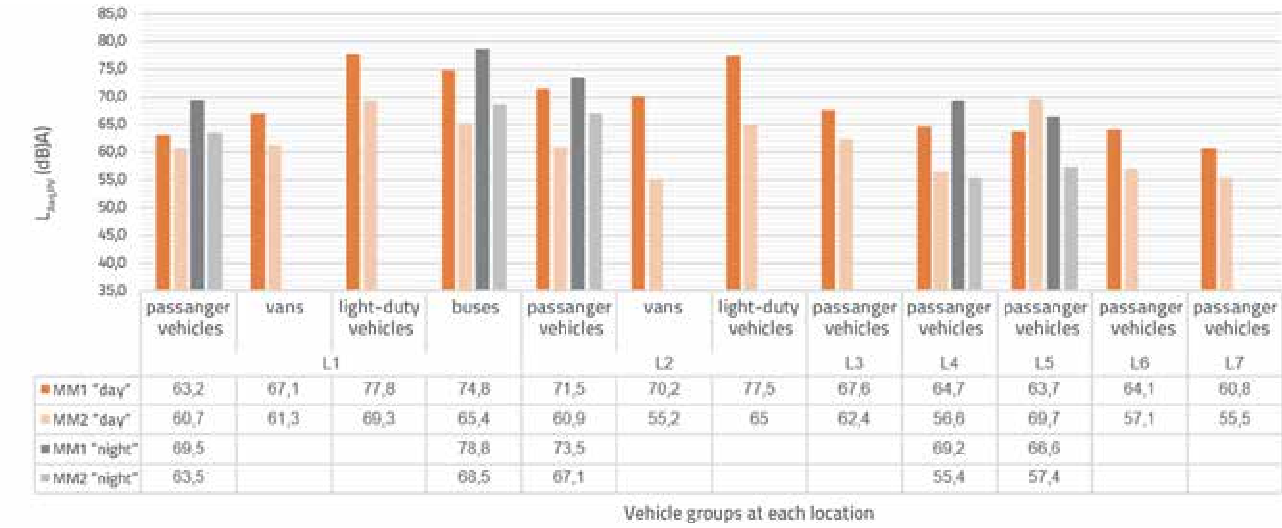

Figure 19. Average noise levels for ten or less successive individual vehicles of a particular group

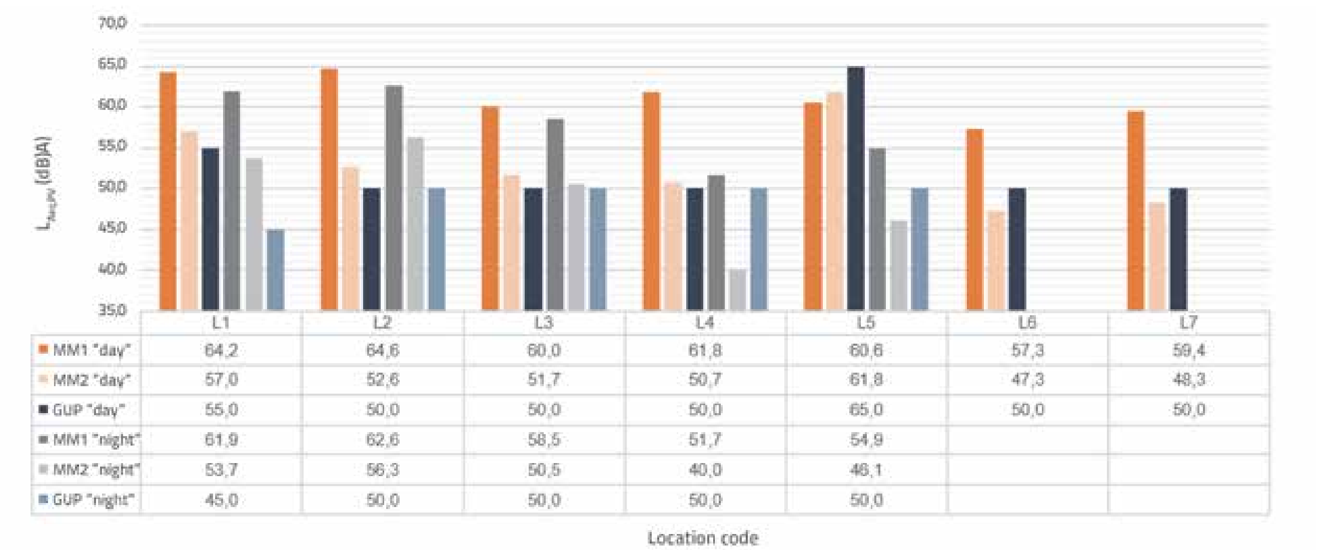

Figure 20. Comparison of equivalent noise levels for all vehicles that passed by measuring points MM1 and MM2

the lowest noise levels are locations L1 and L2. At the location L1, lowest noise levels were generated by passenger vehicles and, at location L2, lowest levels were generated by vans, while the highest noise levels at both locations were generated by light delivery trucks. It can also be noticed that the noise levels of all vehicle groups increased less at location L1 (trapezoidal rubber speed humps), at the spot of the traffic calming device, compared to location L2 (transverse concrete speed hump).

4.2. Equivalent noise levels of all vehicles

The diagram in Figure 20 shows a comparison between equivalent noise levels of all vehicles that passed by the measuring points MM1 and MM2 during a 15-minute timeframe ($L_{Aeq,15}$) in the periods "day" and "night", and the highest allowed planned noise levels specified in the Urban Master Plan (GUP) of the City of Zagreb at the observed locations. The results of the mentioned comparison are described below.

At segments without any traffic calming devices at locations L1, L2, and L3, noise levels during the periods "day" and "night" were higher than allowed (by 2.1 dB(A) on an average during the period "day", and by 5.2 dB(A) during the period "night"), while the noise situation was even less favourable at cross-sections where trapezoidal rubber speed humps, transverse concrete speed bump, and spheroidal elliptical rubber speed bump are located (noise levels were higher by 14.8 dB(A) on an average during the period "day", and by 12.7 dB(A) during the period "night").

At location L4, during the period "day", noise levels were higher than allowed in the cross-section without any traffic calming devices (by 0.7 dB(A)), as well as in the cross-section where the transverse cubic speed hump is located (by 11.8 dB(A)). At the same location, during the period "night", noise levels were lower (by 10.0 dB(A)) in the cross-section without any traffic calming devices, while noise levels were higher than allowed (by 17 dB(A)) in the cross-section where the transverse cubic speed hump is located.

Table 4. Physical obstacles used in the research

Location code	Location code	Material	Height [cm]	Width [cm]
L1	trapezoidal rubber speed hump	rubber	6.8	302.4
L2	transverse concrete speed bump	concrete	3.8	132.9
L3	spheroidal elliptical rubber speed bump	rubber	8.3	299.7
L4	transverse cubic speed bump	concrete	8.8	403.1
L5	transverse rubber speed bump	rubber	8.8	197.7
L6	spheroidal elliptical concrete speed bump	concrete	3.7	316.8
L7	narrow transverse concrete speed bump	concrete	11.4	98.7

Table 5. Influence of various traffic calming obstacle types on current noise situation at analysed locations

Location code	Location code	The change of equivalent noise levels at the spot of the physical obstacle [dB(A)]	
		period "day"	period "night"
L1	trapezoidal rubber speed hump	+ 7.2	+ 8.2
L2	transverse concrete speed bump	+ 12.0	+ 6.3
L3	spheroidal elliptical rubber speed bump	+ 8.3	+ 8.0
L4	transverse cubic speed bump	+ 11.1	+ 11.7
L5	transverse rubber speed bump	- 1.2	+ 8.8
L6	spheroidal elliptical concrete speed bump	+ 10.0	no data
L7	narrow transverse concrete speed bump	+ 11.1	no data

At location L5, during the period "day", noise levels were lower than allowed in the cross-section without any traffic calming devices (by 3.2 dB(A)), as well as in the cross-section where the transverse rubber speed hump is located (for 4.4 dB(A)). It needs to be emphasized that this is the only recorded case in this research where traffic calming devices had a positive impact on the current noise situation. At the same location, during the period "night", noise levels in the cross-section without any traffic calming devices were lower (for 3.9 dB(A)), while in the cross-section in which the transverse rubber speed hump is located noise levels were higher than allowed (for 4.9 dB(A)). Such high noise levels at night, on the spot of the traffic calming devices, were made by cabs, which almost did not reduce their driving speed at all.

Noise levels during the period "day" were lower than allowed (by 2.2 dB(A) on an average) on segments without any traffic calming devices at locations L6 and L7, while the measured noise levels exceeded the allowed values considerably (by 8.6 dB(A) on an average) in cross-sections where spheroidal elliptical rubber speed bumps and a narrow transverse concrete speed bump are located.

5. Discussion and conclusion

The use of physical obstacles for calming traffic can result in a decrease of road traffic noise levels in urban areas. Parameters that influence the corresponding values are: obstacle type, adequacy of construction, choice of location at which the obstacle will be installed, traffic flow structure, drivers' behaviour and traffic signalisation installation method. The impact of various physical obstacle types installed on seven roadways in the City of Zagreb on the current noise situation is analysed in this paper. (Table 4). The research results are presented below (Table 5).

A decrease in noise levels due to crossing of physical obstacles by passenger vehicles was recorded only on the transverse rubber speed bump (L5) during the period "day". During noise measurements at that location, it was noted that all vehicles significantly reduced their driving speed while crossing the speed bump. During the period "night", the opposite happened: all vehicles (mostly cabs) crossed the obstacle at high speed, and therefore higher noise levels were generated in that cross-section compared to the cross-section without any traffic calming devices. However, it is necessary to take into consideration that cab drivers hardly ever slow down at physical obstacles because they often want to reach their customers faster and are driving company vehicles, meaning that they are not worried about car maintenance. In the light of the above, it can be concluded that this physical obstacle has proven to be appropriate for use from the aspect of decrease in road traffic noise levels.

It should be noted that in most cases noise levels actually increased at the locations of other physical obstacles (trapezoidal rubber speed hump (L1), transverse concrete speed bump (L2), spheroidal elliptical rubber speed bump (L3), transverse cubic speed bump (L4), spheroidal elliptical concrete speed bump (L6), and narrow transverse concrete speed bump (L7)). The reason for that is the fact that these obstacles failed to sufficiently motivate the drivers to reduce their driving speed. In fact, only a few passenger vehicles, which decelerated significantly in front of the mentioned obstacles, generated lower noise levels compared to the situation on the segment without any traffic calming devices, while the crossing of the mentioned obstacles by vans, buses, and light delivery trucks resulted in an increase of noise levels in all cases, regardless of how much the vehicles driving in front of them slowed down. Considering the mentioned, the question arises if these physical obstacles contribute to the increase of traffic safety at these locations, which is their primary role, or if they just contribute to worsening of the current noise situation at these locations.

Furthermore, the comparison of average noise levels by vehicle groups at the locations L1 and L2 shows that the lowest noise levels at the location L1 were generated by passenger vehicles, and at the location L2 by vans, while at both observed locations the highest noise levels were generated by light delivery trucks.

The comparison between equivalent noise levels of all vehicles, and the highest allowed planned noise levels specified in the Urban Master Plan (GUP) of the City of Zagreb, shows that noise levels at physical obstacle sites were lower than allowed only at location L5 (transverse rubber speed bump) during the period "day". Nevertheless, it has to be noted that on the given location, considering the purpose of the locality, the value of the threshold noise level for the period "day" is significantly higher than the threshold noise levels for the same period at other observed locations (5 – 10 dB(A)). In other words, despite the fact that the transverse rubber speed bump was the only one that resulted in noise level decrease, if it were installed at any other analysed location, the noise level would be higher than allowed. The biggest increase of equivalent noise levels at the spot of a physical obstacle during the period "day" was recorded at location L2 (12 dB(A)), where the transverse concrete speed bump was installed, while the lowest noise increase was registered at location L1 (7.1 dB(A)) where a trapezoidal rubber speed hump was installed.

Table 4 shows that the analysed speed bumps and speed humps are made of different materials and that they differ in height and width. Considering the mentioned, it cannot a priori be concluded which of the named parameters had the biggest impact on noise levels during the crossing of vehicles. It can however be emphasized that the transverse rubber speed bump (L5), i.e. the only one where a noise level decrease was registered, was the highest and was made of rubber.

In conclusion, it would be advisable to verify credibility of the above described results on a bigger sample and on a greater number of locations and, based on that, to conclude more safely which parameters have the greatest impact on the road traffic noise levels at the locations of traffic calming devices. Furthermore, local and regional authorities should not be the only subjects to decide on the installation of traffic calming devices, i.e. the objections and suggestions of other road users and the broader community should also be taken into consideration. It would also be good to incorporate more detailed instructions regarding such obstacles in relevant regulations (such as the definition of obstacle type as related to traffic flow structure, selection criteria for the location of such obstacles, distance between obstacles, etc.), as the lack of such data often results in excessive and incorrect installation of traffic calming devices.

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