PROTECTIVE AND SAFETY MEASURES AGAINST NEGATIVE EFFECTS OF TRAFFIC NOISE – A REVIEW

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Abstract
Noise represents any unwanted sound that interferes with a person’s work, psychological and health condition, and their rest time. Numerous studies indicate that noise affects changes in human behavior (aggression, social conflicts) and causes stress reactions associated with physiological reactions. It also affects the central and neurovegetative system, reduces attention and concentration ability, reduces work ability, and reduces work productivity. Noise pollution is a major environmental health problem in Europe, with the transport sector being its main cause. The noise level is mostly affected by the number of vehicles, traffic flow, relative share of passenger and freight vehicles, their speed, types and characteristics of the road, whether the traffic is one-way or two-way, intersections, weather conditions, etc. In order to adequately protect against the negative effects of traffic noise, it is necessary to take various measures to reduce it. This paper provides a comprehensive review of the literature with special measures for the protection, monitoring and reduction of the negative impact of traffic noise.

Keywords: traffic, traffic noise, protection measures, noise barriers

1. INTRODUCTION

According to the World Health Organization (WHO), noise is harmful to human health. Numerous studies indicate that noise affects changes in human behavior (aggression, social conflicts) and causes stress reactions associated with physiological reactions. It also affects the central and neurovegetative system, reduces attention and concentration ability, reduces work ability and reduces work productivity (Science Communication Unit, 2015). Noise consequently affects the cardiovascular, immune, and digestive systems, as well as numerous other organs, causing functional disorders. In their study, which focused on the cardiovascular consequences of environmental noise exposure, Münzel and others demonstrated that noise not only causes disturbances, sleep disorders, or reduces the quality of life, but also contributes to a higher prevalence of major cardiovascular risk factors for arterial hypertension and the frequency of cardiovascular diseases. The evidence supporting this claim is based on the established rationale supported by experimental, laboratory and observational field studies and a number of epidemiological studies (Münzel et al., 2014). During their research, Lienhart and others came up with results that show that traffic noise affects physiological reactions during sleep, leading to visible cardiovascular reactions (Lienhart et al., 2018.). Pirrera, De Valek, and Cluydts state in their study that the impact of road traffic noise on sleep and daily functioning causes harmful effects that cannot be ignored. Specific groups such as children, the elderly and the sick are vulnerable and need special attention. Shift and night workers are also at risk because their work schedule
involves sleeping at unusual times, mostly during periods when road traffic noise is greatest (Pirrera et al., 2010). During their research, Singh, Kumari and Sharma list all the harmful effects of traffic noise and finally come to the conclusion that it is high time to take appropriate measures to control noise pollution at the limits of noise exposure (Singh et al., 2018).

Noise pollution is a major environmental health problem in Europe, with the transport sector being its main cause. The noise level is mostly affected by the number of vehicles, traffic flow, the relative share of passenger and freight vehicles, their speed, types, and characteristics of the road, whether the traffic is one-way or two-way, intersections, weather conditions, etc. (Lindov, 2011). The construction of traffic infrastructure, the increase in the number of motor vehicles, the conditions of traffic, and the non-compliance with the legal regulations have led to alarming levels of traffic noise (Lindov, 2003). According to the European Environment Agency (EEA), the most dominant source of noise is road traffic. In 33 EEA-33 member countries, over 110 million people are exposed to noise levels higher than 55dBA caused by road traffic. Of these, 32 million are exposed to very high noise levels (above 65 dB) (European Environment Agency, 2017). In urban areas, 81,668,800 residents are exposed to all-day noise levels caused by road traffic in excess of 55 dB (A), while in suburban areas this number is 31,142,900 (European Environment Agency, 2019). According to the WHO, noise caused by road traffic is the second most harmful source of environmental stress in Europe, right after air pollution. Air traffic contributes only about 1 percent of noise levels higher than 65 dB, to which 80 million people in the European Union are exposed during the day (Zijadić et al., 2014).

It can be stated that traffic noise is considered one of the main causes of reduced quality of life. In order to provide a high-quality environment in which people live and work, control (monitoring) traffic noise, protection measures, and reducing its impact to acceptable levels (up to 55 dBA during the day and 50 dBA at night), are becoming one of the main measures that need to be taken.

2. PROTECTION AND SAFETY MEASURES AGAINST THE NEGATIVE EFFECTS OF TRAFFIC NOISE

This paper provides a comprehensive review of the literature with special measures for the protection, monitoring and reduction of the negative impact of traffic noise. According to the research, there are the following solutions to reduce traffic noise levels:

- noise reduction at the source (vehicle),
- traffic-technical measures and proper planning and construction of roads to reduce noise,
- reducing the impact of noise by setting up protective barriers,
- immission protection measures,
- spatial planning and urban solutions,
- economic measures and legislation.

2.1. Noise reduction at the source (vehicle)

The source of traffic noise consists of vehicles, i.e., vehicle tires in contact with the road surface, engine power, cooling systems, intake and exhaust systems, etc. In the recent years, more and more attention has been paid to reducing acoustic noise in many industrial applications, especially in the automotive industry. Noise reduction is essential as it
contributes to comfort, efficiency and safety. In order to reduce these sources of noise, the European Union adopts regulations, ordinances and directives that vehicle manufacturers are obliged to comply with. One of the strategic goals of the European Union is to halve the negative effects of traffic noise on humans and the environment in the future.

There are two different approaches to achieving noise reduction. On the one hand, the passive approach is widely used. Passive control techniques generally reduce the sound emission of vehicle construction by geometrically modifying and applying additional damping materials. These methods are best suited for a larger frequency range. On the other hand, active techniques are available; these provide an alternative way to minimize unwanted noise resulting from the vehicle construction itself. Active methods are of increasing interest to designers because they are effective and significantly increase construction weight. Active control techniques are usually used in the low frequency range.

Some in-vehicle noise reduction solutions can be classified into:
- measures to improve the acoustic comfort in the vehicle,
- reconstruction and improvement of the intake and exhaust system,
- designing new engine models,
- replacement of fuels (usage of alternatives), and
- reduction of vehicle weight.

Measures to improve the acoustic comfort in the vehicle include better acoustic treatment of the vehicle by insulating the partition wall with the use of vibroacoustic materials. Better isolation of the partition wall on the vehicle means reducing the openings for the passage of cables, wires, and control pedals (gas, brake, clutch), but also by enabling better absorption inside the vehicle. By applying vibroacoustic materials, which are placed on the partition wall, floor, sides and roof of the body, it is possible to reduce the noise by 1 to 2 dB (A), depending on the speed (Lakušić et al., 2005).

Noise reduction by improving the intake and exhaust system is mainly reduced to the use of mufflers, reconstruction of the crankshaft and fan, reconstruction of the catalytic converter, and elastic support of exhaust systems (Milinković & Marjanović, 2009).

In today's engine design process, the acoustics are taken into account at a late stage of development, where the first acoustic measurements can be performed on the final prototype engine. At this stage of development, possible changes in engine design are very limited, and it is therefore impossible to obtain an optimal acoustic solution. This can be overcome by applying various simulations used today in engine designing.

As part of appropriate strategies to reduce the impact of noise from vehicles, it is necessary to take measures that reduce the replacement of fuels, such as: electric vehicles, fuel cell vehicles and hybrid vehicles.

Reducing noise with less vehicle weight means reducing the weight of complete sound packages, applying new materials, passive or active piezoelectric or electromagnetic patches on vehicle and engine panels, using smart Helmholtz resonators and broadband active noise cancellation. When applying these solutions, it is necessary to find full integration and the correct balance of components, in order to achieve the set goals of reducing noise and weight.
2.2. Traffic-technical measures and proper planning and construction of roads to reduce noise

Traffic-technical noise reduction measures include primarily changes in the traffic regime, such as (Lakušić, Dragčević, & Rukavina, 2005):

- traffic calming and
- reduction of traffic load and
- free flow of traffic.

Noise levels can be reduced by calming traffic in residential and other sensitive areas, and the best way is to install devices for automatic speed measurement. In addition, there are other solutions such as placing vertical barriers (raising one part of the road or the entire central space of the intersection, vibrating lanes), narrowing the traffic lane or widening the curbs. Thus, it is possible to achieve noise reduction of 6-8 dB. Traffic calming is possible by adopting new speed limits on roads. The effect of speed reduction on noise is given in the following table.

Table 1. Speed reduction effect on noise (Larsen, 2007)

<table>
<thead>
<tr>
<th>Speed reduction (km/h)</th>
<th>Noise reduction for light vehicles ($L_{aeq}$, dB(A))</th>
<th>Noise reduction for heavy vehicles ($L_{aeq}$, dB(A))</th>
</tr>
</thead>
<tbody>
<tr>
<td>from 130 to 120</td>
<td>-1.0</td>
<td>-</td>
</tr>
<tr>
<td>from 120 to 110</td>
<td>-1.1</td>
<td>-</td>
</tr>
<tr>
<td>from 110 to 100</td>
<td>-1.2</td>
<td>-</td>
</tr>
<tr>
<td>from 100 to 90</td>
<td>-1.3</td>
<td>-1.0</td>
</tr>
<tr>
<td>from 90 to 80</td>
<td>-1.5</td>
<td>-1.1</td>
</tr>
<tr>
<td>from 80 to 70</td>
<td>-1.7</td>
<td>-1.2</td>
</tr>
<tr>
<td>from 70 to 60</td>
<td>-1.9</td>
<td>-1.4</td>
</tr>
<tr>
<td>from 60 to 50</td>
<td>-2.3</td>
<td>-1.7</td>
</tr>
<tr>
<td>from 50 to 40</td>
<td>-2.8</td>
<td>-2.1</td>
</tr>
<tr>
<td>from 40 to 30</td>
<td>-3.6</td>
<td>-2.7</td>
</tr>
</tbody>
</table>

Reduction of traffic load is possible by redirecting traffic to other roads (bypasses). In addition, restricting access to the city center or a specific district (like Superblocks in Barcelona) and even in whole neighborhoods (like Houten in the Netherlands) has proved to be very effective. Restriction or complete ban on the movement of vehicles at certain time intervals is a very good measure to reduce noise, such as limited access to delivery vehicles in the city center outside the morning hours, reservation system for delivery space in the city center (30 minutes with a maximum of two consecutive reservations), prohibited driving at night for trucks, and a ban on the movement of motor vehicles on the roads in order to open periodic pedestrian zones. Relieving traffic in cities, and for the purpose of reducing noise, is possible by promoting and encouraging the use of public city transport, bicycles and other alternative modes of transport. The impact on noise level by reducing traffic load is shown in the following table.
Ensuring the free flow of traffic can be achieved by coordinating traffic lights, while reducing noise resulting from the movement and braking of vehicles. Turning off the traffic lights at night reduces the noise level by up to 4 dB. This measure can, in some cases, be abused by non-compliance with speed limit traffic regulations, so it is best to use it in combination with one of the speed control measures. Free flow of traffic can be achieved by constructing roundabouts instead of installing traffic lights.

The design and construction of routes for the movement of public urban transport vehicles, and in particular rail systems, is also a significant way to reduce noise. The wheel-rail combination must not be neglected when observing noise and vibration propagation. Noise reduction can be achieved in these situations:

- by selection of the appropriate type of superstructure construction,
- by the maintenance of track and wheels,
- by selecting the appropriate vehicle type,
- by reducing the speed of movement.

Traffic noise levels can be reduced by 2 to 4 dB (A) depending on the type and texture of the pavement, such as flat cast asphalt, asphalt concrete and other porous textures. Maintaining the road surface (for example, by leveling canal covers, patching holes and applying a new layer of asphalt) is the most cost-effective and effective corrective method. In this way, the dynamic impacts of the vehicle on the road construction are reduced, which results in a reduction in noise levels. However, this is still a short-term measure, so for example, cracks and damage in the original asphalt pavement reappear on the new layer. Therefore, the road would need to be maintained more frequently if the targeted noise reduction effect is to be achieved. The estimated noise reductions which can be achieved by taking a number of technical measures are given in the following table.

### Table 2. Impact of traffic load reduction on noise (Larsen, 2007)

<table>
<thead>
<tr>
<th>Reduction of traffic load</th>
<th>Noise reduction ($L_{\text{eq}}$, dB(A))</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>0.5</td>
</tr>
<tr>
<td>20%</td>
<td>1.0</td>
</tr>
<tr>
<td>30%</td>
<td>1.6</td>
</tr>
<tr>
<td>40%</td>
<td>2.2</td>
</tr>
<tr>
<td>50%</td>
<td>3.0</td>
</tr>
<tr>
<td>75%</td>
<td>6.0</td>
</tr>
</tbody>
</table>

### Table 3. Estimated reductions in noise levels that can be achieved by traffic-technical measures (Bublin, 2000)

<table>
<thead>
<tr>
<th>Technical measures</th>
<th>Noise reduction (dB(A))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less noisy road surfaces</td>
<td>2 – 4</td>
</tr>
<tr>
<td>Avoid steep slopes of the road</td>
<td>5 – 6</td>
</tr>
<tr>
<td>Walls and other obstacles (the effect depends on the height and position of the obstacle)</td>
<td>5 – 20</td>
</tr>
<tr>
<td>Vegetation screens</td>
<td>4 – 6</td>
</tr>
<tr>
<td>Noise screens (walls and structures of different sizes)</td>
<td>5 – 20</td>
</tr>
<tr>
<td>Galleries</td>
<td>5 – 20</td>
</tr>
</tbody>
</table>
From the aspect of traffic planning, it is necessary to point out the growing trend of development and implementation of sustainable urban mobility plans. These plans are based on the concept of improving the overall quality of life of citizens. Special attention must be paid to the transformation of urban mobility in a way that encourages the transition to the use of mass modes of transport, active mobility (walking and cycling) and the management of transport supply and demand.

2.3. Reducing the impact of noise by setting up protective barriers

If traffic-technical measures and proper planning and construction of roads to reduce noise did not give the desired results, then it is necessary to turn to the construction of appropriate protective structures:

a) horticultural landscaping by planting protective vegetation along the road,

b) protective embankments, 

c) protective walls/barriers, 

d) combination of the above works and facilities, and

e) partial or complete coverage of the road.

In addition to all the benefits it brings, this noise protection measure causes additional investments, as well as shortcomings that affect the environment and driving conditions on the road itself. Some of the disadvantages to keep in mind are:

- the monotony of driving between two walls, 
- difficult integration of facilities into the environment, 
- reducing the comfort of nearby residents due to limited visibility (more recently, it has been addressed by “invisible” sound barriers built of glass or clear plastic).

a) Planting protective vegetation along the road represents the most natural, cheapest, and aesthetically best solution. A minimum of 10 (m) depth of vegetation will result in a noise reduction of only 1 dB (a). Very dense vegetation 30 (m) wide and 200 (m) long can reduce noise by 5dB (A). The following guidelines must be observed when applying this method of protection, alone or in combination with other measures (Kotzen & English, 2019):

- the side of the screen facing the sound source should be made of thick folded curtains of leaves, 
- openings need to be avoided along the entire length of the planting, 
- when planting in special lines, it is necessary to pay attention that the width between the plants remains the same, 
- separation of plantations into special sections need to be avoided, 
- arrangement of plantations in wide individual belts with overlapping or continuous belts with recesses or protrusions does not affect the effectiveness of noise protection, 
- it is recommended to plant evergreen trees because their leaves remain during all seasons.

Spatial constraint can be a problem when planting protective vegetation because it requires occupying a wide belt along the road. However, this is a very cost-effective method,
as the initial and maintenance costs are incomparably lower compared to other protective structures. It is best to apply them in combination with other measures.

Figure 1. Natural landscaping as a measure of noise protection (Abu-Baker et al., 2017)

b) **Noise protection embankments** are the type of construction closest to nature, and are therefore considered an aesthetically acceptable solution, provided that there is sufficient space for its construction. These noise pollution (sound dams) solutions are fully sustainable as they are made from earth, stone or recycled construction waste materials with environmentally relevant ingredients.

The slope of the embankment on the side of the road should be in the ratio 2:3, while the other side of the embankment should be shaped so that the embankment adapts to the terrain. They lower the noise level by about 3dB (A) more than vertical walls of the same height. However, they require a lot of land to build, especially if they are very high (Lindov, 2011). The 5-meter high embankments reduce the noise level by about 6 dB (A).

Figure 2. Earthen embankment (Granova, 2022)

**Steep embankments:** Steep embankments have supporting concrete or stone structures (spatial lattice structures) which are filled with hummus and are greened. Such a supporting structure is designed so that it allows a much steeper slope of the earth or humus embankment. For this reason, embankments are envisaged in cases where there is not enough available space for a real earthen embankment.
c) **Walls / barriers against noise impact** are obstacles that are placed between roads and receivers (urban areas / facilities, etc.). They are most often used because they provide the most effective results in reducing noise propagation. They are the best solution, especially in situations when there is not enough available space for planting protective vegetation and earth embankments. In order to achieve the best possible results, many factors need to be taken into account. First of all, the barriers must be acoustically appropriate. Proper noise barrier design requires consideration from both the acoustic and non-acoustic aspects. From the aspect of acoustic design, it is necessary to think about the barrier material, the place of installation, the dimensions and the shape of the barrier. The decision on the non-acoustic aspect is equally important. Solving one problem (in this case noise) can cause other problems such as unsafe conditions, visibility problems, maintenance difficulties, lack of access to maintenance due to improper barrier design and air pollution in case of complete fencing or covering the space.

By choosing the appropriate height and length of the barrier, it is possible to effectively influence the reduction of noise levels. Barriers do not necessarily always have to be the same height. It depends on the environment and the type of facilities along the road. Changing the height of the barrier can help alleviate the monotonous appearance of longer sections lined with barriers, and can also reduce the visual impact of the barrier. Figure 3 shows the role of the sound barrier in reducing noise levels.

![Figure 3. Influence of barrier on noise reduction (Lärmschutz an Straßen, 2022)](image_url)
The material of construction can be reinforced concrete, concrete, brick, stone, wood, aluminum, glass, transparent plastic and constructions of various materials. The figures show the types of protection walls.
Terraced walls have favorable aesthetic and visual characteristics. They usually consist of reinforced concrete, metal, plastic, reinforced prefabricated structural systems, which are formed into a terraced structure of interconnected chambers, filled with soil and planted with low shrubs, plants or creepers.
The following pictures show the effect of the vertical and cantilever barrier.

Figure 9. Stepped wall; Terraced wall (Durisol, 2022)

Figure 10. Illustration of the effect of the vertical barrier next to the road
Cantilever barriers are barriers with a specially designed part at the top of the barrier. Its function is to reduce the impact of sound waves traveling over the top of the barrier. By comparing 2 (m) high cantilever barriers with a simple flat barrier of the same size, research has shown that the average increase in acoustic protection ranges from 1.4 to 3.6 dB (A).

d) **The combination of the mentioned solutions and facilities** can be chosen for the following reasons:
- available space that is not sufficient for the construction of a protective embankment,
- the available quantities of embankment material are not sufficient,
- the need to avoid the screen type of wall due to aesthetic and visual disturbances,
- breaking the monotony while driving and acting on psychological disorders.

e) **Partial or complete coverage of the road (tunnel or sound tube)** can reduce the noise level by more than 20dB(A) (Kim, Song, Park, & Kim, 2019). Tunnels are completely closed, optimal sound isolation facilities that achieve complete isolation of sound from traffic areas (roads or railways). The tunnels must be long enough to effectively protect the area. They are very expensive to build and usually require high operating costs (lighting, ventilation, fire protection, cleaning, etc.).

A special case of the noise protection tunnel is a simpler design variant - the ZÜBLIN noise protection ceiling. In this case, in the areas along the tunnel and above it can be used efficiently, which enhances the aesthetic appearance and better landscaping (Lärmschutz an Straßen). Applying this solution reduces congestion (exhaust ventilation),
provides natural light and reduces the risk of disaster caused by fire (no retention and spread of smoke).

2.4. Immission noise protection measures (sound isolation)
Noise protection at the site of immission is the measure that is best applied when designing buildings. Sound isolation of apartments includes sound isolation of windows, doors and exterior walls, especially in those parts of the building that are directly exposed to noise. Due to its high cost, it is often considered the last resort to reduce noise at the site of immission, and is especially implemented in noise-sensitive areas. Modern double and triple glazed windows can reduce noise by about 30 dB (A) and even in some cases by 40 dB (A). The acoustic performance of a triple glazing system depends on the quality of the frame used for glazing. In addition to window isolation, the isolation characteristics of door walls are also important. A solid door that fits well can achieve noise reduction between 35 and 40 dB (A) (Murphy & King, 2014).

2.5. Spatial-planning and urban solutions
Spatial-planning and urban solutions suitable for noise protection are (Figure 15) (Bublin, 2000):
- closed construction method,
- terraced construction method,
- atrium construction method and
- construction of buildings as sound isolation.

Reduction of traffic noise by closed construction is provided by the construction of warehouses, shopping malls, business premises and closed garages between residential buildings and noise sources.

Terraced construction method allows the use of a full terrace fence (concrete, glass, etc.), whereby the impact of noise can be effectively reduced.

The atrium construction method, where the garden yards are sheltered from the street, enables relatively quiet living, if the spaces facing the street are adequately protected.

Building as sound isolation means the construction of elongated, compact buildings that connect to each other without leaving space for passage (Städtebauliche Lärmfibel - Hinweise für die Bauleitplanung, 2018). The spaces on the ground floor are not intended for permanent residence of people (warehouses, staircases, work spaces, etc.). This construction method can reduce noise in the range of 25 to 30 dB(A). However, access roads or passages between buildings can only be left if their width is small in relation to the depth of the building. In such circumstances, noise reduction levels are lower.
2.6. Economic measures and legislation

Regulatory-assisted economic protection measures include taxes on vehicles whose noise level exceeds the prescribed values for certain land uses, the establishment of research funds, the development of action plans and implementation of noise protection measures, as well as incentives to encourage noise reduction. Although economic measures have proven to be very effective, they are very limited in European countries.

Legislation should also be supported by appropriate technology. A good example can be seen on the streets of Paris. The first noise radar has been set up in Paris as part of a plan to punish owners of loud motorcycles and other vehicles in one of Europe’s noisiest cities. This device, mounted on a street lighting pole, can measure the noise level of vehicles in motion and identify their license plate. The issuance of fines for excessive noise caused by vehicles is planned for the beginning of 2023. Meanwhile, the government has decided to set up more noise radars in other French cities and test penalty automation procedures as part of the 2019 Mobility Act. Under existing laws, authorities can already sanction owners of noisy vehicles, but police must have the necessary equipment and catch a driver in action. This system works on the principle of speed radar, with automated penalties.

3. CONCLUSION

Numerous studies indicate that noise affects changes in human behavior (aggression, social conflicts) and causes stress reactions associated with physiological reactions. It also affects the central and neurovegetative system, reduces attention and concentration ability, reduces work ability, and reduces work productivity. Noise consequently affects the cardiovascular, immune, and digestive systems, as well as numerous other organs, causing functional disorders. Noise pollution is a major environmental health problem in Europe, with the transport sector being its main cause. According to the European Environment Agency (EEA), the most dominant source of noise...
is road traffic. According to the WHO, noise caused by road traffic is the second most harmful source of environmental stress in Europe, right after air pollution. It can be stated that traffic noise is considered one of the main causes of reduced quality of life. In order to provide a high-quality environment protection measures, and reducing its impact to acceptable levels (up to 55 dBA during the day and 50 dBA at night), are becoming one of the main measures that need to be taken. This paper provides a comprehensive review of the literature with special measures for the protection, monitoring and reduction of the negative impact of traffic noise in six basic groups: reduction of noise at source; traffic technical measures and proper planning and construction of roads to reduce noise; reducing the spread of noise by building protective structures; noise protection at the immission site; spatial planning and urban solutions; economic measures and regulations.

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