DOI: 10.38027/ICCAUA2021164N11

Evaluation of Photovoltaic Noise Barriers in terms of Noise Control - A Case Study from Istanbul

*R.A. MSc **Ferhan Hasmaden** [1], Prof. Dr. **Gülay Zorer Gedik** [2] and Prof. Dr. **Neşe Yüğrük Akdağ** [3]
İstanbul Gedik University, Faculty of Fine Arts and Architecture, Istanbul, Turkey [1]
Yildiz Technical University, Faculty of Architecture, Istanbul, Turkey [2]
Yildiz Technical University, Faculty of Architecture, Istanbul, Turkey [3]
E-mail [1]: ferhanhasmaden@gmail.com, E-mail [2]: ggedik@yildiz.edu.tr, E-mail [3]: nakdağ@yildiz.edu.tr

Abstract
Solar urban design that require no huge space is crucial because of the conflict between real estate value in urban environment and the demand for clean energy need. Noise barriers built-in low-value lands offer potential surfaces for solar panels. Photovoltaic Noise Barrier (PVNB) technology couples noise control structures with renewable energy generation. Double use of structure and land saves material and land. This study aims to determine the effect of noise barrier design variables on the acoustic environment. In the methodology, an existing settlement exposed to highway noise was taken as a sample. In the evaluation phase, only the noise control efficiency has been considered. Noise control performance of PVNB alternatives with different sizes and tilts has been computed with SoundPLAN 7.2. Results show that PVNB noise mitigation performance improves parallel to height and diffraction edge width. Also, the inclination of the edges has a positive correlation with noise reduction.
Keywords: Solar Energy; Noise Control; Photovoltaic Noise Barrier; Noise Barrier; Photovoltaic Panel.

1. Introduction

Environmental noise is an important urban problem and road traffic is the top source of noise pollution. Although noise and energy do not have a direct relationship, the transportation sector accounts for a major share of energy consumption. Total transportation energy represents 29% of global energy consumption and road transport handles %89 of energy for transportation (Navas-Anguita et al., 2019). Globally, urban mobility is projected to be 95% higher in 2050 compared to 2015 (International Transport Forum, 2017). It is estimated that the number of vehicles, which was 11,657 million in 2010, will increase by 116% and reach 25,294 million in 2030 (Solmaz & Çelikten, 2012). The city of Istanbul as a megacity presents a good case for the problem of traffic congestion with population of 14,8 million and centre position of Turkish economic, cultural and historical life. TomTom traffic index 2017 report indicates that Istanbul is the 6th most traffic congested city in the world (Pamucar et al., 2020).
Besides the relationship between transportation and power consumption, transportation has many faces related to environmental pollution. However, two of them are especially weighty: emission of toxic of exhaust gases and vibro-acoustic impacts with high levels of traffic noise (Jacyna et al., 2017). Epidemiological studies have linked noise pollution to health problems (Wolfgang, 2000). World Health Organization data indicated that, at least one million healthy life years are lost every year from traffic-related noise in the western part of Europe (Brambilla et al., 2020). As a result, noise control measures play a key role in heavy traffic urban areas to mitigate the impact of road traffic on energy and noise pollution.
Photovoltaic noise barrier (PVNB) structures in which noise barriers are a sub-structure for solar modules and provide electricity generation aside from noise reduction targets. Through PVNB systems, it is aimed to combine noise barriers with renewable electricity production. Thus, with the dual use of the structure and the land area, material and land savings are achieved. The system highly motivates the electric vehicle market, thereby reducing fossil fuel use and greenhouse gas emissions from the transport industry. PVNB installations which are applied in areas with low-value lands such as roadsides provide both renewable power generation and acoustic comfort for the inhabitants. PVNB technology can overcome the need for extensive areas, which is the biggest disadvantage of solar applications.
In this study, first of all, the factors affecting the performance of PVNB were investigated with a literature review. In this context, design parameters of noise barriers, photovoltaic systems, and environmental impact criteria of sound barriers were determined. As an output of the literature review, various barrier sections were formed with common criteria affecting both solar potential and acoustic behavior of PVNB systems. The scope of the study is to analyze the effect of barrier cross-sections on PVNB performance. The main research problem is determining the effects of barrier dimensions on acoustic comfort according to floor numbers, directions and distances from road of buildings. The evaluations were carried out on a case study. Within the case study, an existing mass housing area threatened to the noise level exceeds the upper value, along a highway with excessive traffic, was taken. The scope of the

assessment is limited to noise control. SoundPLAN 7.2 software was used to calculate the acoustic properties of the noise barrier solutions. Number of receiver points subjected to more than permissible exposure level was accepted as performance indicator for the evaluation of analysis. The analysis results of the barriers was evaluated according to the floors, the distance of the buildings to the barrier, and the facade directions of the blocks. The inclination of the diffraction surfaces, the height of the barrier and the width of the diffraction surface is positively correlated with noise control and has a positive effect even on more problematic floors, facades and blocks.

1.1. Literature Review

The literature review on PVNB has been discussed on three issues: solar energy, noise control, and environmental impact assessment.

Photovoltaic installations should be designed to maximize system output considering the solar energy potential of the system. Many parameters affect the production of photovoltaic systems. These can be compiled as photovoltaic system components, the interaction of components, surrounding circumstances, and design (Usman et al., 2020). Factors that determine the performance of the system are categorized as alterable and non-alterable. Non-alterable features are environmental factors (solar radiation, azimuth, wind flows, amount of precipitation, impact of dust, temperature, and humidity rate), and alterable features are installation design (capacity, panel tilt, module properties, system components) (Mani & Pillai, 2010). Parameters depending on the environment and geographical location are non-alterable; design, installation, and maintenance criteria are alterable.

The scope of the PVNB technology's noise control performance research is defined to road transport. Roadway noise consists chiefly of ground-tire interaction and engine/exhaust system emission (Heutschi et al., 2016). The road-borne noise level depends on three factors: the volume of traffic, the flow of the traffic, and the proportion of heavy vehicles in the traffic flow (Muralikrishna, I. V, Manickam, 2017). Also, meteorological factors have a noticeable effect on the sound level of the environment by affecting the propagation of sound waves (refraction, scattering and absorption in air) (Hallberg et al., 1985). Noise control measures fall into three broad categories: at the source, in the transmission path, and at the receiver (Beranek & Ver, 1992). Noise barriers offer the most effective solution when there is no precaution at the noise source and at the receiver (Garg et al., 2012, 2013). In case of a noise barrier between the source and the receiver, the sound waves come to the receiver by being diffracted from the upper edge of the barrier or transmitted through the barrier (Fard et al., 2013). The effectiveness of the noise barriers depends on various parameters such as the location between the source and the receiver, the length, the height, thickness, or shape of the barrier, the upper edge, and the surrounding ground surface (Redondo et al., 2021). The best location of noise barrier is near the receiver for flat terrain where the road and receivers are at equal heights; however, the final decision should be made with simulations (Andrew et al., 1980). Width and height of the sound walls become the major focus for many researches, since the most important parameter affecting the noise level in the receiver is the path length of diffraction between the source and the receiver (Maekawa, 1968). Studies reveal that adding profiles to the top edge of the vertical barrier increases the insertion loss without a higher sound wall and absorber surfaces (Crombie & Hothersall, 1994; Watts, 1996).

Environmental impact assessments as a performance indicator should also exist in design phase. Environmental impact assessments (EIA) have a key role besides the technical performance of design in newly planned public projects (Tamura et al., 1994). As part of the landscape and environment, the sound barrier can cause environmental impact for drivers and nearby residents. Some studies have shown that most residents living next to the barrier feel that the benefits of barriers predominate the disadvantages (Nilsson & Berglund, 2006). In the meantime, studies have also been conducted to identify occupants' disturbances from the noise barrier due to sense of being confined, limited view, inadequate daylight and ventilation, poor maintenance of the barrier (Fujita et al., 1990, 1991).

The results of the literature review are summarized in Table 1. Non-alterable properties in terms of acoustic environment quality are variables that depend on the highway and environmental conditions such as vehicle volume, a ratio of heavy vehicle, vehicle speeds, road surface characteristics, barrier-road distance, barrier-receiver distance. Non-alterable qualities in terms of solar power potential are characteristics that depend on climatic conditions such as air temperature, global solar radiation, relative humidity, wind flows, amount of precipitation, aspect/direction, and impact of dust. The shading ratio that PVNB structures will create in adjacent blocks depends on the barrier-receiver distance and global solar radiation and is non-alterable. The shading ratio can be reduced by using transparent material in the barrier section. The parameters affecting all three performance indicators are highlighted with a red frame. Variables such as barrier height, barrier length, the tilt of diffraction edge are related to the barrier design. Each barrier design variable has a different effect on performance indicators. The design phase is significant part of the process, in terms of evaluating the effect of design variables on the criteria and determining the optimum solution.

Table 1. Factors affecting PVNB performance indicators

		NONALTERABLE FACTORS													ALTERABLE FACTORS							
		Vehicle Volume	The ratio of Heavy Vehicle	Vehicle Speeds	Road Surface Characteristics	Barrier-Road Distance	Barrier-Receiver Distance	Temperature	Relative Humidity	Amount of Precipitation	Wind Flows (Speed, Directions)	Impact of Dust	Aspect/Direction	Global Solar Radiation	Barrier Length	Barrier Height	The tilt of Diffraction Edge	Width of Diffraction Edge	PV Module Type	System Components	Maintenance	Material (Section Properties)
Performance Indicators	Noise Control Efficiency																					
	Solar Energy Potential																					
	Shading Ratio on Adjacent Blocks																					

2. Methodology and Materials

The case study was performed in a mass housing area located on the side of the roadway with dense traffic and suffers from excessive road noise. Figure 1 shows the site plan and measurement points of the settlement area. The figure also demonstrates the block types and their distance from the highway. The letter codes refer to the typologies of the dwellings. Letters with the same numbers represent blocks equidistant from the barrier. For example; there are 6 blocks with A plan type. There are 2 blocks called A1 and their distance to the highway is equal and 21 meters.

In order to outline the methodology, firstly, the assumptions regarding the study area and the research were made. Then, by designing of PVNB alternatives, barrier cross sections and dimensions identified as used basis of simulation. Finally, the environmental noise modelling and validation phases were performed.

The study grounds on following assumptions;

- The total construction area of the settlement, which is built on approximately 72,000 square meters, is 10,000 square meters.
- The intersection line of the roadway and the settlement is the design area of the PVNB and has an azimuth angle of -30 °.
- Conditions such as traffic flow properties, climatic situation, surroundings, topography, gap between barrier and road are constant in all simulations to demonstrate the effectiveness of PVNB alternatives.
- There are 25 residential blocks with 5 and 9 floors and a 2-storey social facility in the selected area. Storey height is 3 meters in model for all buildings.
- It is envisaged that the residents will use the PVNB installation as an electric vehicle charging station. Therefore, PVNB has been positioned as a parking lot for vehicles and the barrier top width has been modelled 2 m, 3 m, 4 m, and 5 m.
- PVNB length is a fixed modeled parameter in all alternatives with the assumption that PVNB lies between the minor roads in the site plan.
- The height of the garden wall, which is currently at the border of the settlement, varies between 1.80 and 2.50 m depending on the topographic conditions. In the validation part, the model includes the garden wall. In the analysis phase of the barrier variations, the absence of a fence wall was admitted as the base case in order to assess more understandable.
- The vertical wall height of the modeled PVNB structures is 1 m and 2 m.
- The population exposed to traffic noise was calculated assuming that the flats are used at full capacity.
- The distances of the blocks in the settlement to the highway differ among 20 and 194 m.
- Figure 2 gives the flowchart of conceptual framework.

Figure 1. Google Earth view of the case study area (2020) and measurement points.

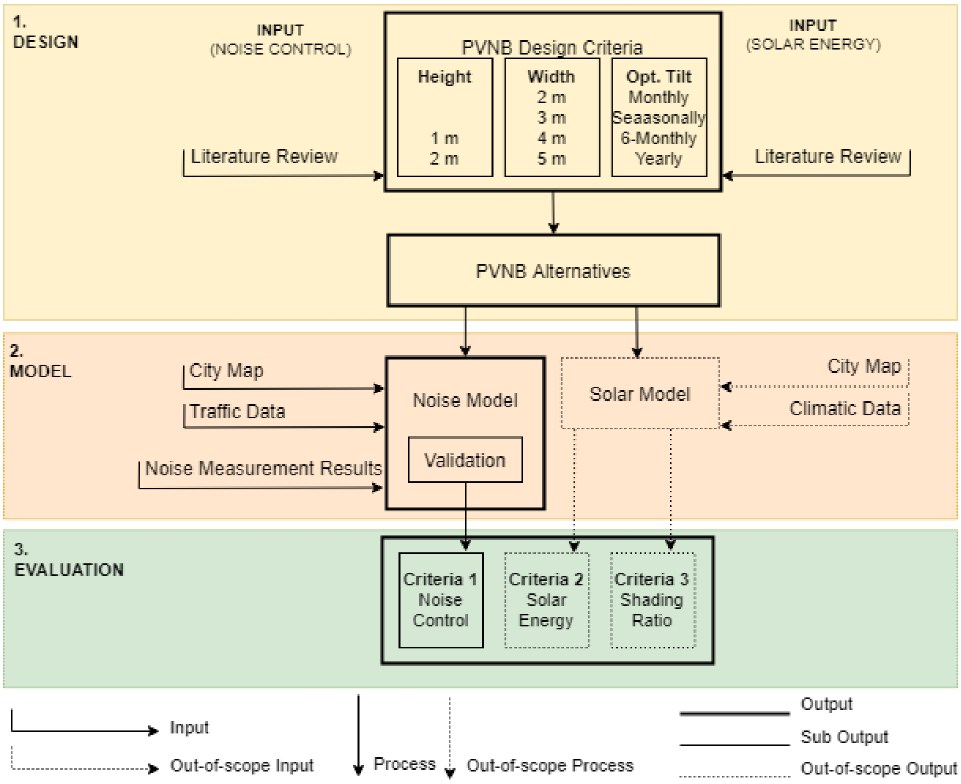


Figure 2. Flowchart of the case study

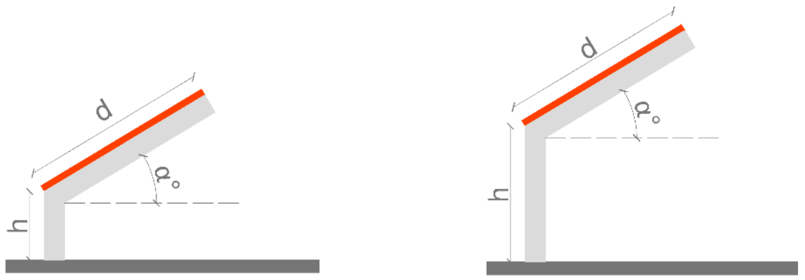
2.1. Design of PVNB Alternatives

The initial assumption is that the PVNB lies between two secondary roads and has a fixed length of 590 m in all calculations. Table 2 shows the PVNB schematic section and design alternatives which have been prepared by changing the common design variables (barrier height, barrier edge, and tilt of barrier edge). Optimization section of PVsyst 6.7.7 software was executed to find out of ideal tilts for different time intervals (monthly, seasonally, semi-annually, and annually). Table 2 also reveals the determined angles for the area with -30° azimuth according to certain intervals. Periodic optimum tilt angles determined for the area were modelled as the tilt of barrier edge in simulation. Panels with an inclination of less than 25° are not included in the calculations due to increased dust accumulation (Lu & Zhao, 2018)

Table 2. Design phase of PVNB alternatives analyzed in the study

Determination of optimum tilt angles		March	April	May	June	July	August	September	October	November	December	January	February
	Monthly (Opt. Tilt, °)	34	27	14	8	15	21	33	45	55	58	53	45
	Seasonally (Opt. Tilt, °)		25			15			43			51	
	Semi-Annual (Opt. Tilt, °)			19						45			
	Annually (Opt. Tilt, °)						31						

Schematic Sections



Barrier Height		h=1 m										h= 2 m									
Alternative No.		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Tilt of Diffraction Edge (°)	α °	27	31	33	34	43	45	51	53	55	58	27	31	33	34	43	45	51	53	55	58
Width of Diffraction Edge (m)	d	2										2									
	d	3										3									
	d	4										4									
	d	5										5									

2.2. Environmental Noise Modelling

The noise maps of the study area were generated in SoundPLAN 7. 2 (Braunstein + Berndt GmbH) sodtware in line with environmental characteristics (building type, number of floors, roads, topographic conditions, etc.), population data and traffic flow properties. The population of the settlement was derived according to the number of rooms in the apartments and transferred to the software.

There are 26 buildings in the settlement area. One of these blocks has 2 floors (social facility), 4 of them have 9 floors (residential, C, 1+1, and 2+1 flats), 6 of them have 5 floors (residence, A, 4+1 flats) and 15 of them have 5 floors (residence, B, 3+1 flats). It has been assumed that the number of residents for each flat is 6 in A-type residences, 5 for each flat in B-type residences, 3 for 2+1 apartments and 2 for 1+1 apartments in C-type residences. The total population of the settlement was determined as 1480 by calculating with Equation 1.

$$n_i = \sum_{i=1}^{n} \alpha\, b\, p_{\alpha b} \qquad \text{Equation 1}$$

n : Number of Blocks
α : Number of Floors
b : Number of Flats on each floor
$p_{\alpha b}$: Number of residents in each flat

Istanbul Transportation Department provided data on annual hourly traffic flow such as vehicle volume, vehicle classification and vehicle speeds. According to the sum of the hourly data obtained from the traffic monitoring device closest to the settlement, the annual amount of vehicles passing on the highway is 34,946,809 and the volume of vehicles passing during the day is 23.852.818 and the ratio of heavy vehicles is 12.7%. The total data was converted to hourly values and defined in SoundPLAN as traffic volume per hour, heavy vehicle ratio. The average speed of

vehicles using the road during the day is also available and the average speed is 75 km/h for light vehicles and 72 km/h for heavy vehicles.
According to the conversion of the data to the daily traffic volume, the Annual Average Daily Traffic (ADDT) is 95,744. The road is one of the densest highways according to benchmark of the General Directorate of Highways. In the noise simulations, the traffic data of the minor roads in the region are also included in the calculations.
Meteorology parameters which are also important for sound speed and air absorption were defined to SoundPLAN. Climate inputs of Istanbul were assigned in the software respectively; dominant wind directions are NNE and SSW, the annual average temperature is 13.9 and the mean relative humidity is 71.5%.
It is recommended to use the NMPB-Routes-96 calculation method within the European Union Directive 2002/49 / EC and the Regulation on the Assessment and Management of Environmental Noise for noise mapping (Assessment and Management of Environmental Noise (EU Directive), 2002) (Regulation of Environmental Noise Assessment and Management, 2010). The method is based on the Guide de Bruit guide and considers the meteorological conditions as suggested in the ISO 9613 standard (CETUR, 1980; ISO 9613-1, 1993).
The lane width of the divided road was 3.5 m, the road slope was 0% and road surface was entered as asphalt into software. Noise maps shall reveal the sound level distribution at a height of 4 m from the ground as required by the European Union Environmental Noise Directive (Assessment and Management of Environmental Noise (EU Directive), 2002). In the meantime, it also states in appendix 1 that other heights may be used for local design measures, provided that the height from the ground is not less than 1.5 meters. Calculation point height is taken as 1.5 m, which is accepted as the average height of ear level (standing), due to noise reduction assessment in open areas to be made within the scope of the study (Akdağ et al., 2017).
In pursuance of the Good Practice Guide for Strategic Noise Mapping and the Production of Associated Data on Noise Exposure, a grid spacing of 10 x 10 is sufficient whereas in a city environment 5x5 grid spacing may be better (WG-AEN, 2007). Noise mapping was adjusted according to 5 meters grid spacing as stated in the guide since a congested urban area was evaluated within the scope of the study. The daytime average noise level, Lday, (over a 12-hour period, 07:00-19:00) was taken into account to evaluate the noise reduction efficiency of the PVNB structure simultaneously with the solar potential. Photovoltaic panels require sunlight to generate electricity, noise maps have not been calculated for the evening and night time intervals.
Figure 3 reveals the current noise climate of the case study area. The most practical method for verification procedure of environmental noise simulations is comparing simulated and measured values (İlgürel et al., 2016). The probabilistic nature of the traffic complicates the modelling and measurement of traffic noise. The noise level measurement result includes the noise produced by independent noise sources (industry, residents, animals, etc.) in addition to traffic noise (Prezelj & Murovec, 2017). In environmental noise prediction, uncertainty is defined as the difference between measurement results and simulation outputs.

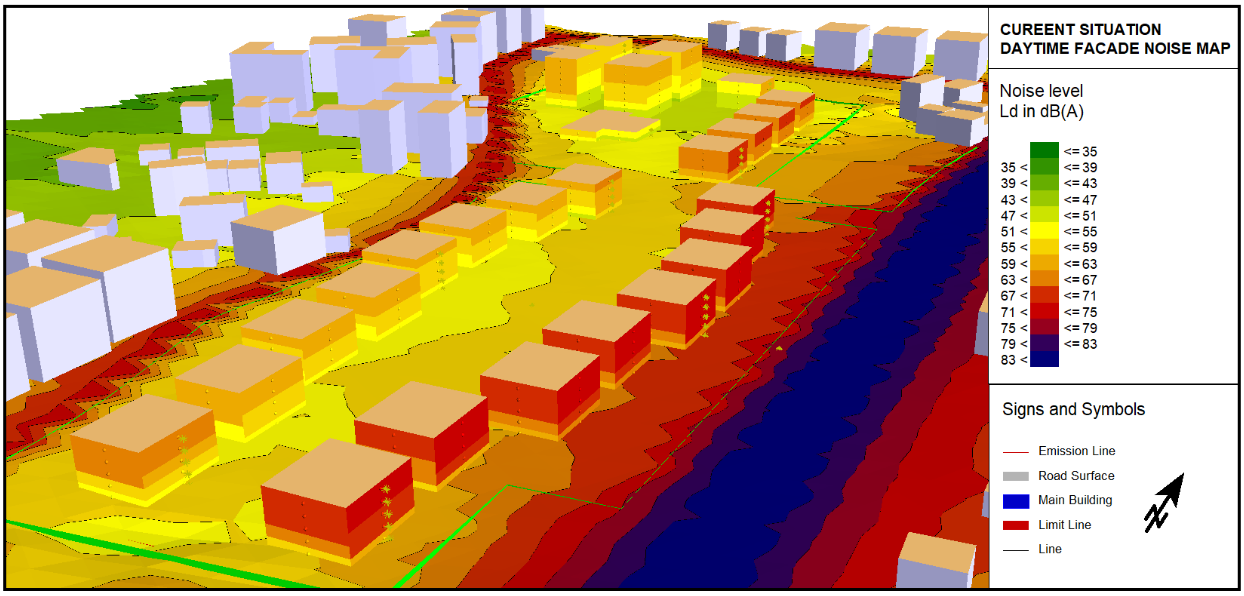


Figure 3. Current situation façade and grid noise map for daytime interval

According to the simulation experiments of Maruyama et al., when the number of vehicles crossing the highway is more than 170, the permissible error (ΔLAeqT) should fall within the range of ±1 dBA (Maruyama et al., 2013). In some studies, intermediate estimation error between the measurement results and calculation outputs should be between ± 3 dBA and ± 5 dBA (Bastián-Monarca et al., 2016; Lee et al., 2008; Vukadin et al., 2008). This range may be associated to psychoacoustic surveys where the 3 dBA difference in the noise level under controlled conditions is perceptible by the average human and the 5 dBA difference corresponds to the detectible difference in the daily background sound level (Bell & Bell, 1994; Bies et al., 2018). Maximum difference between noise measurements points with respective receivers in the software should be 1 dBA for 300 meters from the road, 3 dBA for 600 meters from the road and 10 dBA for 2,000-3,000 meters from the road as asserted in the guideline (WG-AEN, 2007). The most realistic characterization of environmental parameters (topography, buildings, surrounding masses and surface properties of ground) and traffic features (proportion of heavy vehicles, vehicle speed and vehicle volume) let greater accuracy in noise maps.

The environmental noise measurement was conducted in accordance with ISO 1996-1 standard that guides for the management of measurement processes (ISO 1996-1:2003. Acoustics–Description et al., n.d.). The environmental noise measurement was performed on midweek afternoon in the frequency range A and Bruel&Kajer Type 2236 was used as sound level measurement instrument. Measurements were made 1.5m above ground level with a microphone windscreen, at least 2m away from buildings to prevent any surface reflection. Sound pressure level (LAeq) measurements were made at 12 points shown in Figure 1 at a height of 1.5 m from the ground and at least 2 meters from buildings. Table 3 shows the 5-minute sound level monitoring results of the measurement points and the simulation outputs of the receiver points at the same location.

Table 3. Noise measurement results and simulation outputs at reference points

Measurement points	1	2	3	4	5	6	7	8	9	10	11	12	STD DEV.
Distance to the highway	36	21	41	95	110	98	70	115	200	134	77	2	
Measured LAEq	64,7	67,2	61,8	55,1	55,9	56,7	57,8	56	49,7	51,7	57,5	78,4	7,77
Calculated Laeq	64,8	67,1	61,3	54,1	52,1	55,6	58,7	51,1	46	49,4	56	77,8	8,82
Difference	+0,1	-0,1	-0,5	-1,0	-3,8	-1,1	+0,9	-4,9	-3,7	-2,3	-1,5	-0,6	1,60

Table 3 displays the measured and simulated values at the reference points. The difference between the values is in the range of ±1 dBA at the 4 points closest to the highway. However, the difference is above the reliable range due to the uninterfered noise sources near the receiver points during the measurement process increasing the environmental noise level.

Turkey's official regulation, Environmental Noise Assessment and Management Regulation, which was prepared in 2005 pursuant to the European Directive, was revised and entered into force on 04.06.2010 (Assessment and Management of Environmental Noise (EU Directive), 2002), (Regulation of Environmental Noise Assessment and Management, 2010). The regulation points out 63 dBA limit noise level during daytime interval for the case study area.

Figure 3 demonstrates the daytime noise map of the facades. The noise level of the central receiver defined on each floor of the building blocks is expressed in the facade noise maps. The facade noise map presents the noise levels of 580 computation points. 240 of these points are on the facades of 12 street blocks where traffic noise is dominant. The inferences may be drawn in line with the simulation outputs are as follows;

- Excessive noise levels (above 63 dBA) were observed in 24% of all receptors in the settlement and 55% of street blocks' receptors.
- According to the simulation outputs of the facades where the highway noise is maximum, 39% of all blocks; 88% of the first row blocks isubjected to permissible limit. Noise control is critical as there are bedrooms on the frontal facades.
- 14% of the population are exposed to unacceptable levels of noise. This ratio rises to 31% when only street blocks are evaluated.
- The daytime noise level limit in open areas is specified as 55 dBA in the regulation. Accordingly, the noise level in 44% of the garden exceeds the acceptable value.
- Finally, the facade noise level distributions were evaluated according to the floors. As a result, it was observed that 12% of the receivers on the 1st floor and 73% of the receivers on the 5th floor exceeded the allowable noise level.

3. Findings and Discussion

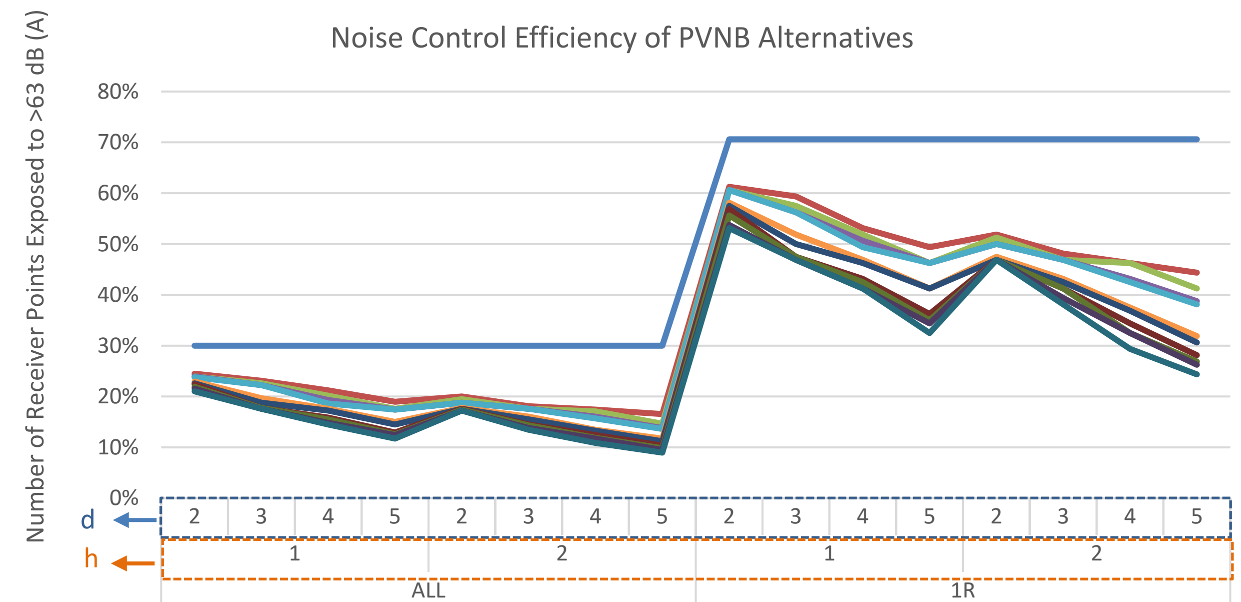
3.1. Findings

80 PVNB alternatives have been modelled for the case study in SoundPLAN 7.2 software and their noise control performances are discussed. Acoustic comfort conditions of the residential blocks vary depending on their distance to the highway traffic noise. The evaluations are partly divided into 2 groups: (i) blocks in the first row with no masses between the barrier and traffic noise predominant along, (ii) all buildings in the settlement. In the graphs, "1R" represents the buildings in the first row and "ALL" represents all blocks in the settlement. The first row comprises A1, A2, A3 and B1 blocks, as Figure 1 shows. Although B2 blocks are also in the front row, they aren't included in 1R blocks because of the masses between them and the road and the noise barrier is not long enough.

During the analysis of the simulation data, a general evaluation has been made first. To examine in detail the effect of barrier variables on noise reduction in the settlement, the assessment has been handled in three different frameworks; (i) floors, (ii) distances to the barrier, (iii) facade directions. Simulation outputs have been evaluated according to the receiver point ratio above the limit noise level and have been shown on the vertical axis in the graphs. Horizontal axis of graphs shows the barrier design variables. The *h* is the height of the vertical section of the barrier and is simulated in the study as 1 m and 2 m. d is the width of the diffraction edge of barriers and is modeled as 2 m, 3 m, 4 m, and 5 m. Tilt of diffraction edges of the barrier alternatives appears in the legend part of the graphs.

Figure 4 shows the effect of barrier alternatives by plotting the quantity of receivers exceeding the acceptable level in all blocks and street blocks. The vertical axis in the graph expresses the ratio of the sum of receptors subjected to noise levels greater than limit value to the total number of receivers. The lower amount of receptor points exceeded permissible exposure limit means the better the barrier performance. The horizontal axis refers to the height of the vertical section and the width of the diffraction edge. The effect of barrier top inclination angles shown with colours below the graph and barrier alternatives of various sizes on noise control was investigated. The blue line, denoted by "0" in the legend, indicates the acoustic climate in the absence of any noise barriers. Graphics and findings showing the general condition are below;

- In the case "0", 30% of the receiver points in the all blocks and 71% of the receiver points of the front blocks suffer from the noise level above the limit value.
- The performance of the sound barrier increases parallel to the width of the diffraction edge and the inclination angle of edge.
- Higher height (h= 2 m) alternatives provide acoustic comfort at more receiving points.
- h=1 m, d=2 m, and 27° inclined alternative provide the lowest improvement in noise reduction. h= 2 m, d= 5 m and 58° tilted one achieve the highest improvement in the simulation area. When all blocks are evaluated, 24% of receiver points with the least effective barrier type, and 9% of the receivers with the most effective barrier type subjected to greater noise level than permissible exposure limit. When street blocks are evaluated, 61% of the receiver points with the least effective barrier type, and 24% of the receivers with the strongest effective barrier type are exposed to noise above permissible limit.
- The barrier alternative having maximum performance improves noise reduction by 21% in all blocks, and it improves 46% in the first row blocks.
- Barrier alternatives with a steeper and wider diffraction edges provide greater improvement in noise control. For example, when all settlement blocks are evaluated for h=2 m barrier type, increasing the edge width of the 27° tilted barrier from 2 m to 5 m improves the performance of its by 17,2%. The Noise barrier performs 48% better when the edge width of the 58 ° inclined barrier is increased from 2 m to 5 m.
- There are situations where barrier alternatives with different cross sections show the same performance. For example, h = 1 m, d = 5 m and 31 ° and h = 2 m, d = 3 m and 31 ° inclined barrier alternatives provide equal acoustic comfort in all blocks. This is due to the barrier alternatives of equal or similar height.
- Results show that alternatives with a slope of 34 ° -58 ° provide more improvement than those with a slope of 27 ° -34 °.



	2	3	4	5	2	3	4	5	2	3	4	5	2	3	4	5
h	1				2				1				2			
	ALL								1R							
0°	30%	30%	30%	30%	30%	30%	30%	30%	71%	71%	71%	71%	71%	71%	71%	71%
27°	24%	23%	21%	19%	20%	18%	17%	17%	61%	59%	53%	49%	52%	48%	46%	44%
31°	24%	23%	20%	18%	19%	18%	17%	15%	61%	58%	52%	46%	51%	47%	46%	41%
33°	24%	22%	19%	17%	19%	18%	16%	14%	61%	56%	51%	46%	50%	47%	43%	39%
34°	24%	22%	19%	17%	19%	18%	16%	14%	61%	56%	49%	46%	50%	47%	43%	38%
43°	23%	20%	18%	15%	18%	16%	13%	12%	58%	52%	47%	41%	48%	43%	38%	32%
45°	23%	19%	17%	14%	18%	16%	13%	11%	58%	50%	46%	41%	47%	43%	37%	31%
51°	22%	18%	16%	13%	18%	14%	12%	10%	57%	48%	43%	36%	47%	41%	34%	28%
53°	22%	18%	16%	13%	17%	14%	12%	10%	56%	48%	43%	35%	47%	41%	33%	27%
55°	22%	18%	15%	12%	17%	14%	12%	9%	54%	47%	41%	34%	47%	39%	33%	26%
58°	21%	18%	14%	12%	17%	13%	11%	9%	53%	47%	41%	33%	47%	38%	29%	24%

Barrier Alternatives

0° 27° 31° 33° 34° 43° 45° 51° 53° 55° 58°

(h : height of barrier , d : width of barrier edge)

Figure 4. Noise control efficiency of PVNB alternatives on the case study area

The effects of PVNB alternatives on acoustic comfort on floors are evaluated. The noise levels of the receivers on the southeast facade of the block closest to the highway are analyzed. Figure 5 shows the data of the first analysis group. The vertical axis refers to the noise level, the horizontal axis refers to the barrier alternatives. The blue line in the legend is the noise level of the floors on the southeast side of the closest (21 m from the highway) block, in the absence of any noise barrier. The following conclusions have pointed out in the evaluation:

- In the base case denoted by “0”, the 5th floor is the floor that is exposed to the most noise.
- While 58° tilted barrier top provides the highest contribution to noise reduction, 27° tilted barrier top is the lowest.
- Observations show that the width of the diffraction edge and the height of the vertical section increase the noise mitigation in the upper floors.
- All the PVNB alternatives manage to reduce the noise level below 63 dBA on the 1st floor. Most of the alternatives with h= 2 m achieve acceptable noise levels on the 2nd floor. On the 3rd floor, only wider, higher, and steeper ones provide the limit noise value. However, none of them can meet the acceptable conditions for the 4th and 5th floors.
- ± 3 dBA difference in noise level is the threshold value that detectable by the human ear. In this context, 100% of the alternatives provide useful noise reduction on the first floor, 92,5% on the second floor, 31,25% on the third floor, and 1,25% on the fourth floor. When the noise levels on the fifth floor are examined, it is seen that no barrier alternative provides beneficial noise reduction.

- The effect of the barrier type providing maximum noise reduction (h=2 m, d=5 m, 58° tilted) on floors has been evaluated. The noise level decreases by 7.4 dBA for the first floor, 11.9 dBA for the second floor, 8.6 dBA for the third floor, 3,3 dBA for the fourth floor, and 0.6 dBA for the 5th floor.
- PVNB alternatives achieve the most improvement on the 1st floor and the least improvement on the 5th floor.
- The effects of the best and worst alternatives have been compared. h=1 m, d=2 m and 27° tilted barrier, reduces amount of receptors experienced the excessive noise level, by 65% on the 1st floor, and 17% on the 2nd floor. No improvement has been observed on the 3rd, 4th and 5th floors. Barrier type with h=2 m, d=5 m, and 58° tilted provides 100% improvement on the 1st and 2nd floor, 75% on the 3rd floor, 46% on the 4th floor, and 17% on the 5th floor.
- Almost all of the alternatives provide acoustic comfort on the 1st floor, even low height and low width alternatives. In the 2nd and the following floors, the effectiveness of barriers with low height and less width decreases.
- On the 5th floor, barrier alternatives with a height of h= 2 m and a diffraction edge width of over 3 meters, and an inclination angle of over 51° slightly mitigate the noise exposure.
- It is important to position the high-rise blocks away from the highway, as the noise reduction on the upper floors is relatively little compared to the lower floors.

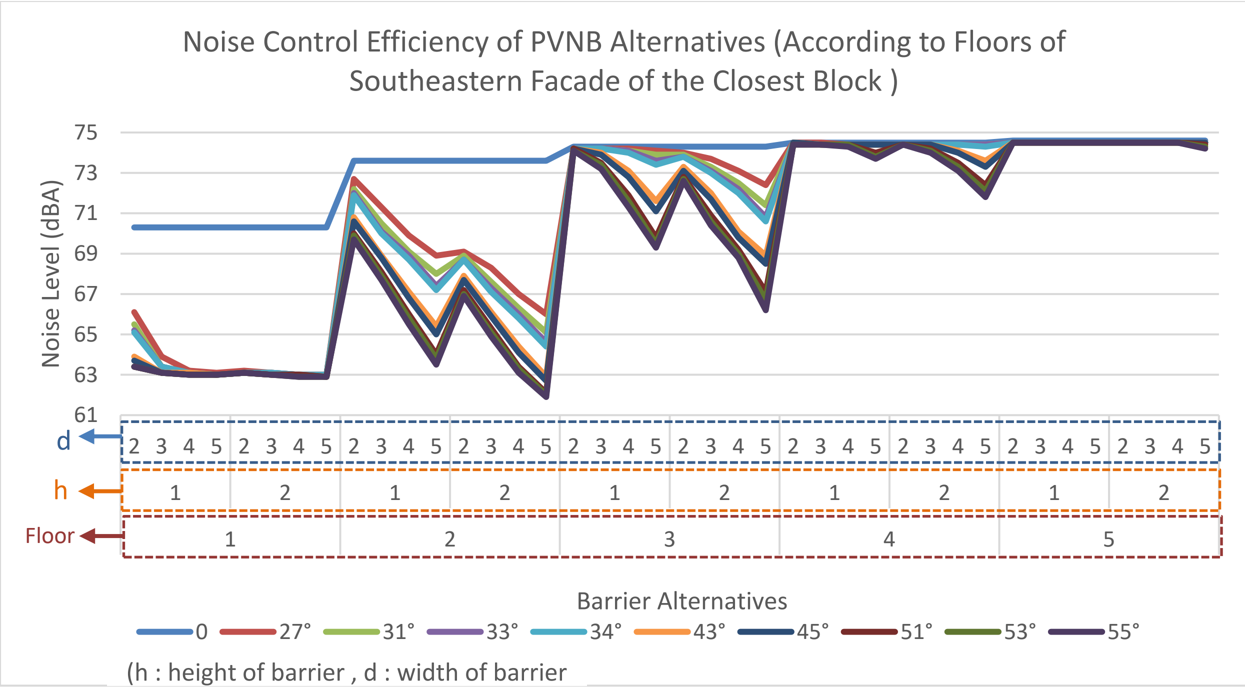


Figure 5. Noise control efficiency of PVNB alternatives according to floors of the southeastern facade of the closest block

To observe the effect of PVNB alternatives on buildings at different distances from the highway, the ratio of first row blocks to the overall number of receivers subjected to sound level more than the limit level has been analyzed. Figure 6 illustrates the investigation results. The base case where there is no control measure is the blue line indicated with "0". The implications are as follows;

- Blocks at a distance of 21 m and 29 m from the PVNB are exposed to maximum noise, while blocks at a distance of 41 m are exposed to the lowest noise, as seen in the base case.
- Alternatives with higher vertical elements, wider diffraction surfaces, and steeper tilted ones provide a beneficial reduction ratio in blocks at 21 m, 29 m, and 36 m distances.
- In the base case, in blocks with distances of 21 m, 29 m, 36 m, and 41 m to the barrier, the percentages of receiver points above limit level are 75%, 75%, 70%, and 62%, respectively. With the barrier alternative providing maximum noise reduction (h=2 m, d=5 m, 58°), the rates of receptors suffered from excessive noise level are 32%, 35%, 25%, and 10%.
- The observations are that the greatest improvement proportionally occurred in the furthest blocks to the PVNB. The reason for this is that the noise level in the distant blocks is lower relative to the ones close to the noise source and it is easier to fall below the limit value.

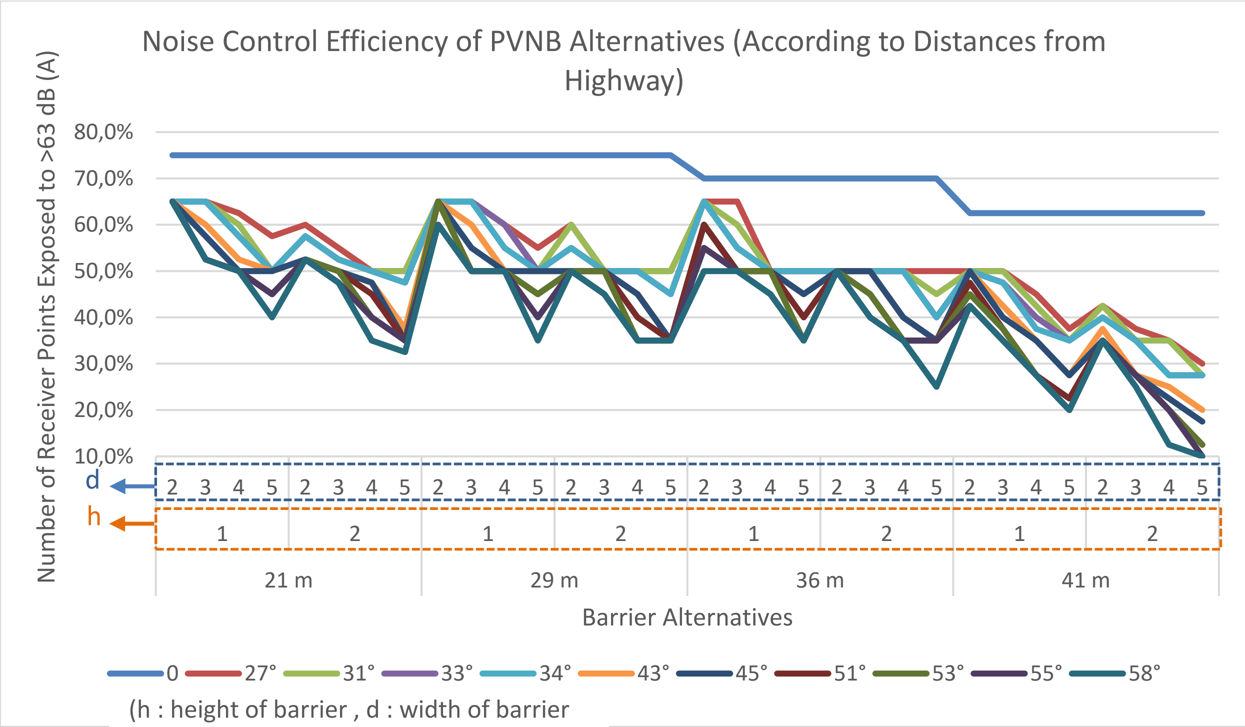


Figure 6. The effect of PVNB alternatives on noise levels in blocks at different distances from the barrier

To observe the effect of PVNB alternatives on facade directions, we have analyzed the ratio of the total amount of receivers exposed to noise above the limit level for first row blocks. In this group, A1, A2, A3, and B1 blocks where traffic noise is dominant have been considered. Figure 7 displays the analysis results. The base case where there is no control measure is the blue line indicated with "0". The results of the examination are as follows;

- The southeast facade, parallel to the highway, exposes to maximum noise.
- Northwest facade of all blocks at different distances from the highway, have comfortable sound environment. The limit value is not exceeded, as the receivers on the northwest facade are in the acoustic shadow zone.
- The barrier alternative that provides maximum noise reduction (h=2 m, d=5 m, 58°) achieves% 43 improvements on the southeast facade. The same alternative provides an average 70% improvement on the northeast and southwest sides.

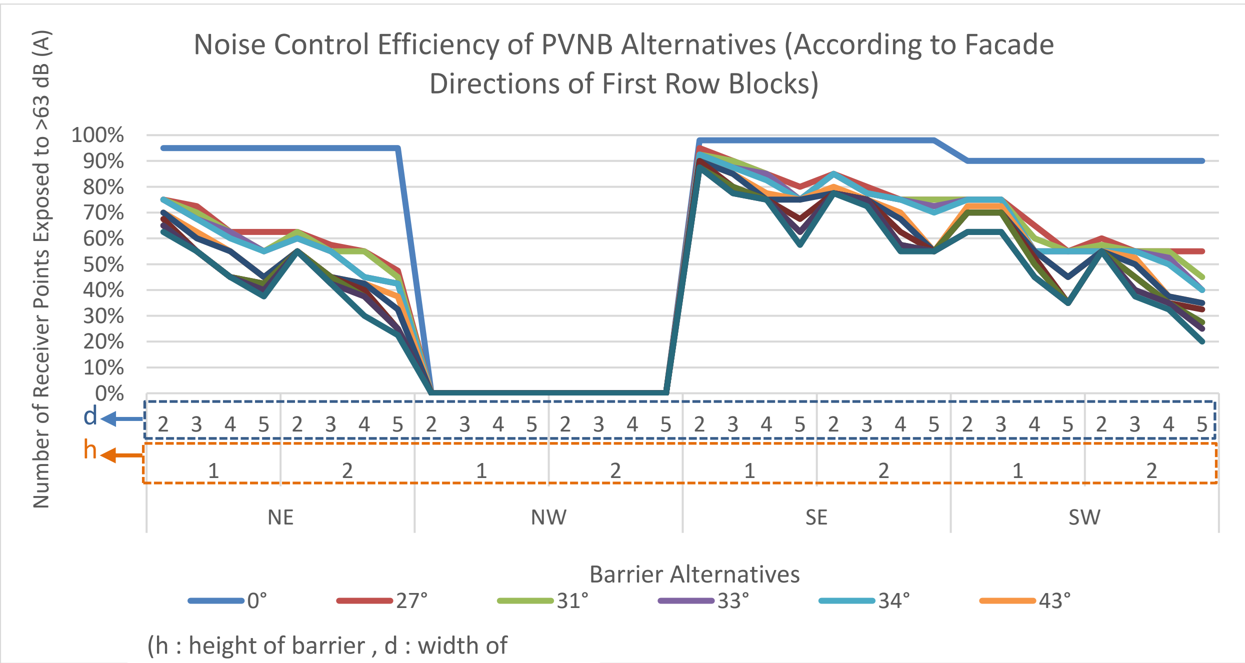


Figure 7. The effect of PVNB alternatives on noise levels according to facade directions

3.2. Discussion

The results regarding the noise control behaviour of barrier alternatives analyzed from various aspects are as follows;

- The "number of receiving points exposed to 63 dBA noise" criterion indicates the amount of receptors experienced the sound levels more than the legal limit, and the alternatives with the minimum number of points are evaluated as high performance.
- The best alternative in terms of acoustic attenuation is the 58 ° inclined barrier with maximum height and diffraction surface width (h = 2, d = 5, 58 °). It ensures the acceptable noise level at extra 122 receiver point compared to the base case.
- The noise control efficiency of barriers increases parallel to the height of the vertical section and the width of the diffraction surface.
- The inclination of the diffraction surfaces is positively correlated with noise control. Steeper angles improve noise control efficiency.
- High-rise buildings located away from the motorway provide protection of more populations from noise and reduce noise exposure on higher floors.
- In the spatial planning step, spaces that are tolerant to noise should be planned on facades that are parallel to the highway. The facades in the acoustic shadow zone are suitable for noise sensitive areas in the plan layout.

Table 4 gives a matrix summarizing the effects of PVNB alternatives. Simulation outputs of the 58 ° inclined barrier has been taken as reference because of the best acoustic attenuation performance. Cell values represent the receiver point ratio above the limit noise level according to evaluation for general, evaluation by floors, by distances and, by directions. Low percentages in green indicates less noise problem. Higher percentages in red indicate dense populations exposed to excessive noise.

Table 4. Summary matrix showing the impact of PVNB alternatives

		General	Floors					Distances				Directions			
h (m)	d (m)		1	2	3	4	5	21	29	36	41	NE	NW	SE	SW
0	0	71%	53%	75%	75%	75%	75%	75%	75%	70%	62%	95%	0	98%	90%
1	2	53%	9%	41%	66%	75%	75%	65%	60%	50%	42%	63%	0%	88%	63%
1	3	47%	3%	19%	63%	75%	75%	52%	50%	50%	35%	55%	0%	78%	63%
1	4	41%	0%	19%	47%	66%	75%	50%	50%	45%	27%	45%	0%	75%	45%
1	5	33%	0%	3%	22%	63%	75%	40%	35%	35%	20%	38%	0%	58%	35%
2	2	47%	3%	19%	63%	75%	75%	52%	50%	50%	35%	55%	0%	78%	55%
2	3	38%	0%	16%	38%	63%	75%	47%	45%	50%	25%	43%	0%	73%	38%
2	4	29%	0%	0%	19%	63%	66%	35%	35%	40%	12%	30%	0%	55%	33%
2	5	24%	0%	0%	19%	41%	63%	32%	35%	35%	10%	23%	0%	55%	20%

4. Conclusion

The conflict between the need of large areas for clean energy and the scarcity of empty urban lands has made the effective use of brownfieds essential. The use of noise barriers located in dysfunctional areas as sub-structures for photovoltaic modules provides acoustic comfort as well as meeting the city's clean energy needs.

This research targeted the examination the effect of photovoltaic noise barrier design variables on noise control performance. Solar energy and shading ratio criteria are beyond the scope of the research. The noise control performance of PVNB alternatives is evaluated based on the amount of receivers subjected to sound levels more than the permissible exposure limit.

First, the barrier design variables that affect the PVNB performance have been determined with the literature review in the study. Barrier height, the width of the diffraction edge, and tilt of the diffraction edge are common design variables that affect all performance indicators. The ideal inclination angles of the PVNB structures were determined for different time intervals (annually, semi-annually, seasonally and monthly) in line with the azimuth of the study area and solar radiation data. 80 alternatives have been created by deriving design variables such as widths of diffraction surfaces of the barrier, inclination angles, and barrier heights and evaluated within noise control criteria.

The case study presents a conceptual framework for solar noise barrier designs. It guides designers in determining the most effective cross-section under different conditions such as environmental conditions, noise level, settlement layouts.
The foresight of increasing the need for mobility caused by population growth and urbanization, necessitates further studies on PVNB technology to create social and environmental benefits in cities. Prioritizing solar energy and noise control in areas where PVNB technology is envisaged affects design decisions. A criticality index that determines criteria weights should be developed in terms of both physical environmental factors. Sensitivity analysis investigating the effect of barrier design parameters on budget and performance will be useful in making critical design decisions. The trade-off between lifetime costs and cost of benefits is decisive in payback period and project decisions of photovoltaic noise barriers. Due to the limited charging station and long charging time, which are the biggest handicaps in electric vehicle use, the role of the proposed technologies in making driving forces for adoption of electric cars should be investigated.

Acknowledgements
No specific subsidies were received from the public, commercial or non-profit funding agencies for this study.

Conflict of Interests
No conflict of interest has been declared by the authors.

References

Akdağ, N. Y., Gedik, G. Z., Kiraz, F., & Şener, B. (2017). Effect of mass housing settlement type on the comfortable open areas in terms of noise. *Environmental Monitoring and Assessment*, *189*(10), 1–12. https://doi.org/10.1007/s10661-017-6202-1

Andrew, C., May, D. N., & Osman, M. M. (1980). Highway noise barrier location for maximum benefit/cost. *Journal of Sound and Vibration*, *71*(1), 59–64. https://doi.org/10.1016/0022-460X(80)90408-3

Arenas, C., Leiva, C., Vilches, L. F., & Cifuentes, H. (2013). Use of co-combustion bottom ash to design an acoustic absorbing material for highway noise barriers. *Waste Management*, *33*(11), 2316–2321. https://doi.org/10.1016/j.wasman.2013.07.008

Bastián-Monarca, N. A., Suárez, E., & Arenas, J. P. (2016). Assessment of methods for simplified traffic noise mapping of small cities: Casework of the city of Valdivia, Chile. *Science of the Total Environment*, *550*, 439–448. https://doi.org/10.1016/j.scitotenv.2016.01.139

Bell, L., & Bell, D. (1994). Levels and Spectra. In *Industrial Noise Control* (2nd ed., pp. 37–66). Marcel Dekker.

Beranek, L. L., & Ver, I. L. (1992). Noise and vibration control engineering. In *John Wiley & Sons* (Vol. 12, Issue 11). https://doi.org/10.1109/MPER.1992.161424

Bies, D., Hansen, C., & Howard, C. (2018). The Human Ear. In *Engineering Noise Control* (pp. 56–93). Spon Press.

Brambilla, G., Benocci, R., Confalonieri, C., Roman, H. E., & Zambon, G. (2020). Classification of urban road traffic noise based on sound energy and eventfulness indicators. *Applied Sciences (Switzerland)*, *10*(7). https://doi.org/10.3390/app10072451

Guide du Bruit des Transports Terrestres [Land Transport Noise Guide - Forecasting noise levels], (1980).

Crombie, D. H., & Hothersall, D. C. (1994). The performance of multiple noise barriers. In *Journal of Sound and Vibration* (Vol. 176, Issue 4, pp. 459–473). https://doi.org/10.1006/jsvi.1994.1389

Assessment and management of environmental noise (EU Directive), Official Journal of the European Communities 12 (2002). https://doi.org/10.1016/j.jclepro.2010.02.014

Fard, S. M., Kessissoglou, N., Samuels, S., & Burgess, M. (2013). A review of road traffic barriers for low frequency noise. *Proceedings of Meetings on Acoustics*, *19*, 1–6. https://doi.org/10.1121/1.4800975

Fujita, S., Koi, H., & Tamura, H. (1990). Analysis of the group preference for the environmental impact of heavy road traffic. *Trans. Inst. Syst. Control Inf. Engineers*, *3*(8), 237–244.

Fujita, S., Koi, H., & Tamura, H. (1991). Evaluation of countermeasures for preventing environmental impact of heavy road traffic and modeling of consensus formation between two conflicting groups. *Trans. Inst. Syst. Control Inf. Engineers, 4(5)*, *4*(5), 196–203.

Garg, N., Kumar, A., & Maji, S. (2013). Significance and implications of airborne sound insulation criteria in building elements for traffic noise abatement. *Applied Acoustics*, *74*(12), 1429–1435. https://doi.org/10.1016/j.apacoust.2013.05.012

Garg, N., Sharma, O., Mohanan, V., & Maji, S. (2012). Passive noise control measures for traffic noise abatement in Delhi, India. *Journal of Scientific and Industrial Research*, *71*(3), 226–234.

Hallberg, B., Larsson, C., & lsraelsson, S. (1985). Measurements of meteorological effects on long-range sound propagation using m-sequence correlation. *Journal of the Acoustical Society of America*, *78*(3), 1038–1044.

https://doi.org/10.1121/1.393021

Heutschi, K., Bühlmann, E., & Oertli, J. (2016). Options for reducing noise from roads and railway lines. *Transportation Research Part A: Policy and Practice*, *94*, 308–322. https://doi.org/10.1016/j.tra.2016.09.019

İlgürel, N., Yüğrük Akdağ, N., & Akdağ, A. (2016). Evaluation of noise exposure before and after noise barriers, a simulation study in Istanbul. *Journal of Environmental Engineering and Landscape Management*, *24*(4), 293–302. https://doi.org/10.3846/16486897.2016.1184671

International Transport Forum. (2017). *ITF Transport Outlook 2017*. https://doi.org/https://doi.org/10.1787/9789282108000-en

Ising, H., & Kruppa, B. (2004). Health effects caused by noise: Evidence in the literature from the past 25 years. *Noise and Health*, *6*(22), 5–13.

International Standard International Standard, 9613-1 (1993).

ISO 1996-1:2003. Acoustics – Description, measurement and assessment, of environmental noise – part 1: basic quantities and, & Procedures., A. (n.d.). International Standard International Standard. *International Organization for Standardization*.

Jacyna, M., Wasiak, M., Lewczuk, K., & Karoń, G. (2017). Noise and environmental pollution from transport: Decisive problems in developing ecologically efficient transport systems. *Journal of Vibroengineering*, *19*(7), 5639–5655. https://doi.org/10.21595/jve.2017.19371

Lee, S. W., Chang, S. Il, & Park, Y. M. (2008). Utilizing noise mapping for environmental impact assessment in a downtown redevelopment area of Seoul, Korea. *Applied Acoustics*, *69*(8), 704–714. https://doi.org/10.1016/j.apacoust.2007.02.009

Lu, H., & Zhao, W. (2018). Effects of particle sizes and tilt angles on dust deposition characteristics of a ground-mounted solar photovoltaic system. *Applied Energy*, *220*(October 2017), 514–526. https://doi.org/10.1016/j.apenergy.2018.03.095

Maekawa, Z. (1968). Noise r e d u c t i o n by screens*. *Applied Acoustics*, *1*(3), 157–173. https://doi.org/10.1016/0003-682X(68)90020-0

Mani, M., & Pillai, R. (2010). Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations. *Renewable and Sustainable Energy Reviews*, *14*(9), 3124–3131. https://doi.org/10.1016/j.rser.2010.07.065

Maruyama, M., Kuno, K., & Sone, T. (2013). The minimum measurement time for estimating LAeqT of road traffic noise from the number of vehicle pass-bys. *Applied Acoustics*, *74*(3), 317–324. https://doi.org/10.1016/j.apacoust.2012.08.005

Muralikrishna, I. V, Manickam, V. (2017). Noise pollution and its control. In *BS Publications* (pp. 399–429). https://doi.org/10.1016/b978-0-12-811989-1.00015-4

Navas-Anguita, Z., García-Gusano, D., & Iribarren, D. (2019). A review of techno-economic data for road transportation fuels. *Renewable and Sustainable Energy Reviews*, *112*(September 2018), 11–26. https://doi.org/10.1016/j.rser.2019.05.041

Nilsson, M. E., & Berglund, B. (2006). Soundscape quality in suburban green areas and city parks. *Acta Acustica United with Acustica*, *92*(6), 903–911.

Ouis, D. (2002). Annoyance caused by exposure to road traffic noise: An update. *Noise and Health*, *4*(15), 69–72.

Pamucar, D., Deveci, M., Canıtez, F., & Lukovac, V. (2020). Selecting an airport ground access mode using novel fuzzy LBWA-WASPAS-H decision making model. *Engineering Applications of Artificial Intelligence*, *93*(April), 103703. https://doi.org/10.1016/j.engappai.2020.103703

Prezelj, J., & Murovec, J. (2017). Traffic noise modelling and measurement: Inter-laboratory comparison. *Applied Acoustics*, *127*(December 2017), 160–168. https://doi.org/10.1016/j.apacoust.2017.06.010

Redondo, J., Peiró-Torres, M. P., Llinares, C., Bravo, J. M., Pereira, A., & Amado-Mendes, P. (2021). Correlation between objective and subjective assessment of noise barriers. *Applied Acoustics*, *172*, 107640. https://doi.org/10.1016/j.apacoust.2020.107640

Regulation of Environmental Noise Assessment and Management, No. 25862. The Official Gazette (2010). https://www.mevzuat.gov.tr/File/GeneratePdf?mevzuatNo=14012&mevzuatTur=KurumVeKurulusYonetmeligi&mevzuatTertip=5

Solmaz, H., & Çelikten, I. (2012). Estimation of amount of pollutants generated by vehicles in turkey until 2030. *Gazi University Journal of Science*, *25*(2), 495–503.

Tamura, H., Fujita, S. ichi, & Koi, H. (1994). Decision analysis for environmental impact assessment and consensus formation among conflicting multiple agents - including case studies for road traffic. *Science of the Total Environment, The*, *153*(3), 203–210. https://doi.org/10.1016/0048-9697(94)90199-6

Usman, Z., Tah, J., Abanda, H., & Nche, C. (2020). A critical appraisal of pv-systems' performance. *Buildings*, *10*(11), 1–23. https://doi.org/10.3390/buildings10110192

Vukadin, P., Bublić, I., & Tudor, I. (2008). Urban noise mapping - an approach to the establishment of standard making procedure. *The Journal of the Acoustical Society of America*, *123*, 3031. https://doi.org/10.1121/1.2932683

Watts, G. R. (1996). Acoustic performance of a multiple edge noise barrier profile at motorway sites. *Applied Acoustics*, *47*(1), 47–66. https://doi.org/10.1016/0003-682X(95)00030-D

WG-AEN. (2007). *Position Paper: Good Practice Guide for Strategic Noise Mapping and the Production of Associated Data on Noise Exposure* (Issue August).

Wolfgang, B. (2000). Traffic Noise and Cardiovascular Disease: Epidemiological Review and Synthesis. *Noise&Health*, *2*(8), 9–32.