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Full Length Research Paper

A case study on acoustic performance and construction costs of noise barriers

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In the study, the barriers used for reducing traffic noise are being examined in means of performance and construction cost. First a noise prediction is made in the sample highway under certain traffic conditions in order to determine the noise barrier requirement and the results are confirmed by measurement. According to the noise prediction equations used in Turkey, Germany and Canada, the effects of heavy vehicle ratio, average traffic flow speed and hourly total vehicle quantity change on noise level and barrier requirement are examined, so assessment can be made for highways having different traffic specifications than the sample highway. In the continuation of the study, the working principle of noise barriers and effects of barrier position and height on reducing noise are researched in order to determine the construction costs of barriers in Turkey and Canada at different heights and made from different materials.

Key words: Highway, noise barrier, noise prediction, performance, construction cost.

INTRODUCTION

Sound is a physical phenomenon that is caused by air pressure waves, emanated from a vibrating source, and alerts the hearing sense of human beings. While sound is an energy type that emits waves, noise is simply an unwanted sound. The magnitude of the highway traffic noise being analyzed in this study is drastically affected by the engine type of the vehicle, friction, velocity, road properties, and traffic volume. Discrete sources, caused by vehicles in a flowing traffic, turn into a linear source, which is the most stable source of all known random noise sources in the city, and causes a discomforting feeling at high levels (Beranek, 1971). Mitigation strategies are needed to be developed to eliminate the discomfort and bring down the noise level to proper values. People exposed to high traffic noise increases day by day. In Europe, the number of people exposed to noise levels leading to serious annoyance, speech interference and sleep disturbance is about 450 million (EEA, 2003). To protect people from hazard of traffic noise high levels, there are regulations and threshold values to control the noise even though they vary from country to country. The legislation in Turkey that concerns noise control is the 'Evaluation and Management of Environmental Noise Regulation' issued by the Ministry of Environment and Forestry on 1st of July, 2005.

The objective of this regulation is "to create an environment that will not threaten the peace and tranquility, and physical and mental health of the public by unwanted noise" as defined in the regulation. According to this regulation, environmental traffic noise levels, L_{day} and L_{night}, should not exceed the threshold values given in Table 1 (Turkish Republic Regulation of

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Table 1. Acceptable noise levels in Turkey.

Location	Renewed/repaired ways		Present ways	
	L_{day} (dBA)	L_{night} (dBA)	L_{day} (dBA)	L_{night} (dBA)
Urban areas	55	45	60	50
Noise sensitive areas (educational and cultural buildings and hospitals, skilled care institutions) summer house areas and camping areas	60	50	65	55
Residential area	63	53	68	58
Trade and residential areas	65	55	70	60
Industrial areas	67	57	72	62

Ministry of Environment and Forestry, 2005). The aim of this study is to search for the effect of a noise barrier position on the cost and acoustical effectiveness of noise barrier.

In terms of country administration systems, Turkey and Canada have a big difference. While Canada has a federal government, Turkey does not. Most Canadian laws are regional, managed by municipalities and differ from one another. According to Ontario Noise Assessment Criteria in Land Use Planning: Requirements, Procedures and Implementation (Ontario Ministry of the Environment, 1997), if the outdoor living area sound level is less than 55 dB(A), no control measures are required. If it is higher than 60 dB(A), then the noise level should be reduced to the level of 55 dB(A) with some measures, such as a noise barrier with a minimum surface density of 20 kg/m^2.

The criteria for using noise barriers addressed in the regulation are as follows: "The operating agency/organization takes precautions for the following conditions: locations proximate to highways with an annual traffic of three million vehicles, areas where the number of complaints due to noise generated by dense population and highways are considerably high and noise level L_{day} exceeds 68 dB(A). For this purpose, effective and applicable precautions should be taken to prevent the houses nearby the highway from the noise exposure. Techniques such as reducing traffic flow, selecting different road pavement, and installing noise barriers on the roadsides (in compliance with TS EN 1793-1, TS EN 1793-2 and TS EN 1793-3 Standards) should be taken into consideration" (Turkish Regulation TS 9315, 2005).

First, noise level should be determined to scrutinize the necessity of these precautions. While noise level can be measured manually, there are also estimation techniques based on computations to determine the noise level. A mathematical expression to predict the noise level should reflect the correction factors as accurate as possible. Since the factors vary from country to country and are dependent on the features of the applied region, the area, where empirical formula will be applied, should be mathematically defined. Specifically main factors, such as the source of the noise, noise reduction factors (for example, noise reduction effect of earth and air), and topography, should be included in the formula. Prediction methods should be further developed with the aid of designed computer programs. It is possible to acquire early information on acoustic performance of new roads and barriers to be installed on them, particularly during the road planning/design stage, by using these computer programs (Calis, 2007).

There are several methods to decrease the traffic noise requiring various construction and maintenance costs. The effectiveness and cost comparison of different precautions to decrease traffic noise are given in Tables 2 and 3.

Previous studies regarding noise barriers included topics such as functionality, economic analysis, and comparisons with other precaution methods (Sanderg and Ejsmont, 2002; Reynolds, 1992; YTMK, 1995; DMRB, 2012; Watts et al., 1999; Ekinci, 2004; Ozturk, 1992; Meiarashi, 2004), noise barrier types, the significance of the barrier locations (Northdurft, 1989; Hauck, 1979), prevention costs, and the performance of the noise barriers (Kotzen, 2009; Rütrih 1983; Monazzam and Lam, 2005; Koussa et al., 2012 ; Naish et al., 2011) were examined by many researchers in the implementations conducted in order to decrease the noise caused by the traffic (RTR, 1995; Collie et al., 1994; Corb, 1990; Nijland et al., 2003; Avsar and Gonullu, 2005).

Moreover, the cost comparisons of the curtains in relation with other precautions and studies directed towards economical evaluations were implemented by some associations and individuals (UIC, 2004; Reynolds, 1992; Hodgson and Busch, 1997). Qdais and Qudais (2000), for instance, implemented a noise model for traffic in Jordan while Qudais and Alhiary (2007) also implemented a noise model for the signalized intersections.

In previous studies, it is mostly discussed that the shape of the noise barriers, mathematical modeling of noise barrier behavior, other precaution methods using

Table 2. Comparison of different types of traffic noise precautions (YTMK, 1995).

Precaustion type	Effectiveness	Cost comparison
Earth berm / embankment	Acoustically same as noise barriers but requires much land use	Cheapest solution if fill materials and land use are avaliable
Noise barrier (wood, Concrete, Metal or other)	Acoustiaclly good and	10 to 100 times expensive than earth berms
Cut-and-cover tunnel	Suggested for heavy vehicle traffic routes	80 to1600 times expensive than earth berms
Double glass application	Only effective when all windows are closed	5 to 60 times expensive than earth berms

Table 3. Comparison of different types of traffic noise preacaustions (DMRB, 1995).

Barrier Type	Assumed features of design	Relative Cost
Earth mound	- Agricultural land price, landscape planting excluded - Local source of fill assumed	Very low
Timber screen	-Designed in accordance with current standards	Low
Concrete screen	- Precast pier, beams and panels	Fairly low
Brickwork/ masonry wall	- Standard facing brick	Moderate
Plastic/ planted system	- Plastic building ‘blocks’ (planters)	Moderate
Metal panels	-Plastic coated metal panels with steel supports	Moderate
Absorbent panels	- Perforated (absorbent) metal panels with rockwool infill	Moderate
Transparent panels	- Steel piers, etched glass panels	Fairly high
Crib wall	- Proprietary system or purpose designed - High labour costs, agricultural land price	Very high

present structural elements like building façades or balconies, combined effects of noise barriers and porous pavements. All experimental or computational studies held the subject with different aspects of noise barriers but this study differs from other studies in the way not only showing comparison of traffic noise models in use for different countries but also discussing the position of the barrier in the view of cost and effectiveness with respect to location between noise source and receiver. Moreover, this study varies from other studies in the manner of cost calculation of noise barriers both by using published the national price units and by comparison of different height of barriers.

In this study, a road section was taken as a sample. Turkish, Canadian and German traffic noise prediction methods were verified with site work. Then, the noise barrier features according to different traffic flow conditions, such as heavy vehicle ratio, average traffic flow speed, total vehicle number, were determined. After the analysis of the working principle of noise barriers and the effect of location and height of noise barriers on receiver, economics of noise barriers with different height and material were searched for Turkey and Canada. This study differs from previous studies in a manner of originality and will theoretically and practically help people who are interested in noise barriers.

MATERIALS AND METHODS

Traffic noise prediction

The calculation formulae used by most prediction models are very similar. Basically, a reference noise level, corresponding to the noise level due to a single vehicle running under the standard conditions at a reference distance, is obtained experimentally and incorporated into the formula as a constant value. Correction factors are used to allow for the influence of the types of vehicles, traffic flow, average speed, distance, type of pavement, ground absorption, road cross section, screening effect of obstacles, etc. The number and values of these factors vary from one model to another.

Traffic noise prediction methods of the study

In this study, traffic noise prediction methods of three different countries are used: Turkey, Germany and Canada. First the equations of the prediction methods are given and then traffic noise levels of known conditions are predicted with respect to accepted variable. In the end, the prediction results are compared with site study results.

This study utilized the French (Guide du bruit) method's mathematical formulas included in the "Road Noise Reduction" report and equations found in the "Noise Guide", which are used for newly built roads in France. Therefore, in the prediction of traffic noise, the same guide lays the foundation of Noise Control Regulation in Turkey (HNGR, 2010; Turkish Standard 1993; Schroter and Chiu 1997).

Turkish / French noise prediction method

The mathematical formula used to predict sound levels generated by traffic on newly-built town roads and dual carriageways are similar to the formula proposed in the French 'Guide du bruit' (GB), that is, Since Turkey is a member of OECD, the noise prediction equation used by France was accepted when the Regulations were prepared.

$$L_{eq} = 20 + 10.\log(Q_{VL} + E.Q_{VP}) + 20.\log\left(d + \frac{l_C}{3}\right) + 10.\log\left(\frac{\theta}{180}\right) \quad (1)$$

The parameters in Equation 1 that are used in the noise prediction are; L_{eq}: noise level at (d) distance to the roadside, Q_{VL}: number of light vehicles, Q_{VP}: number of heavy vehicles, E: factor of acoustic equivalence between light vehicles (≤3.5 t) and heavy vehicles (≥3.5 t), V: average velocity (km/h), d: distance to the roadside (m), lC: width of the roadway in meters, θ: angle at which the road is seen (in degrees) (OECD, 1995; Calis, 2007).

German noise prediction method

In Germany, a document entitled 'Directives for Anti-noise Protections along Roads (RLS-90) published by the Road Construction Section of the Federal Ministry for Transport, provides a method for predicting noise levels generated by road traffic and a method for designing anti-noise barriers. The noise prediction Equations 2-8 used by the method (RLS) is: (OECD, 1995; Ozturk, 1994).

$$L_m, A = L_m^{(25)} + \Delta L_{st} + \Delta L_v + \Delta L_k + \Delta L_{stg} + \Delta A \quad \text{(dBA)} \quad (2)$$

$$L_m^{(25)} = 37.3 + 10.\log\,[M(1 + 0.082\,p)] \quad (3)$$

$$\Delta L_v = L_{pkw} - 37.3 + 10.\log\left[\frac{[100 + (10^{0.1\,L} - 1).p]}{100 + 8.23.p}\right] \quad (4)$$

$$L_{pkw} = 27.7 + 10.\log\,(1 + (0.02V_{pkw})^3] \quad (5)$$

$$L_{Lkw} = 23.1 + 12.5\log\,(V_{Lkw}) \quad (6)$$

$$L = L_{Lkw} - L_{pkw} \quad (7)$$

$$\Delta A = 15.8 - 10\log(A_1) - 0.0142\,(A_1)^{0.9} \quad (8)$$

L_m,A: average road traffic noise level, M: number of total vehicles, P: heavy vehicles ratio in number of total vehicles, Lm $^{(25)}$: noise level at 25 m from the source, ΔL_{st}: pavement effect factor in noise, this value is zero for smooth, new placed pavements, ΔL_v: the noise effect of cruising speed on the way depending on the ratio of heavy vehicles, V_{Lkw}: heavy vehicles speed, V_{pkw}: light vehicles speed, ΔL_k: the noise effect of junction on the research section of the road (there is no junction in this study, so ΔL_k:0), ΔL_{stg}: the noise effect of inclination of the research section of the road (up to 5%, ΔL_{stg}:0), ΔA : the correction factor according to the distance to the axis of the road, and A_1: distance to the axis of road (m).

Canadian noise prediction method (ORNAMENT)

STAMINA and ORNAMENT (Ontario Road Noise Analysis Method for Environment and Transportation) are the only two methods approved by Ontario Ministry of the Environment (MOE) and Ontario Ministry of Transportation (MTO) to use in the prediction of the traffic noise (Ontario Ministry of Transportation 2006). The Equations 9-12 given below are taken from ORNAMENT and valid for reflective surfaces.

$$L_{eq} = 10.\log(V_{ref}) + 10.\log(D_{ref}) - 10.\log(S) - 25 + 10.\log\,(P_A 10^{(L_0)_A/10} + \mathrm{P_{MT}}.10^{(L_0)_{MT}/10} + \mathrm{P_{HT}}.10^{(L_0)_{HT}/10}) + 10.\log\left(\frac{D_{ref}}{D}\right) + 10.\log\left(\frac{V}{V_{ref}}\right) + 10.\log\left(\frac{\theta_2 - \theta_1}{180}\right) \quad (9)$$

V_{ref}: reference traffic volume (40 vph), D_{ref}: reference distance (15 m), S: traffic flow speed (km/h),
$(L_0)_A$, $(L_0)_{MT}$, $(L_0)_{HT}$ are reference energy mean emission sound levels of automobiles, medium trucks and heavy trucks and given in Equations 10-12, P_A, P_{MT}, P_{HT} are percentages of automobiles, medium trucks and heavy trucks, D is the distance between line source and receiver, V is the traffic volume, θ_2 and θ_1 are expressed in degree and define the extent of the road segment at the receiver location.

$$(L_0)_A = 38.1\log(S) - 2.4 \quad (10)$$

$$(L_0)_{MT} = 33.9\log(S) + 16.4 \quad (11)$$

$$(L_0)_{HT} = 24.6\log(S) + 38.5 \quad (12)$$

Model selection and the results of noise prediction

There are numerous calculations formula for the prediction of the road traffic noise level. Three of them were selected in this study for predicting the noise levels for specific conditions.

In this research, Sehit Ilhanlar Street at Sahrayı Cedit, Istanbul was chosen as the case study area. This street has an average of 2% slope, two 7.5 m width lanes, and a total of 1000 vehicles that use the road with an average of 80 km/h flow speed (IBB, 2008). Assuming that noise distributes equally in every direction, noise reduction values were computed independent from the variables that affect the noise distribution in open air, such as wind velocity and direction, and air temperature. Since the buildings have gardens in this street, the distance between the road and the receiver is approximately 27 m. Therefore, the distance of the receiver to the road was selected as 27 m, respectively for all computations.

Three methods have some differences regarding the data input. To eliminate these differences, some data were converted into the same type of data. The German (R.L.S) method for predicting noise levels uses the flow speed of each vehicle group (both light and heavy vehicles) in the calculation of traffic flow speed. In this case, the traffic flow was calculated as the weighted average speed. The speed of each vehicle group was multiplied by its number; and then the sum of multiplication results of each group was divided by the total number of vehicles (Kutlu, 1993; Bernstein, 1984). In Canadian method calculations, the heavy vehicle ratio is shared equally to both medium trucks and heavy trucks.

According to the comparison of the results, the French (G.B) method was observed to produce more traffic noise than the German (R.L.S) and Canadian (ORNAMENT) methods.

According to these results, noise level predictions for the specific traffic conditions, based on Equations 1, 2 and 9 (Report, 1995; Turkish Standard TS9315, 2005), were performed in this study. The physical properties of the barrier to be installed, which is based on the predicted noise level and threshold value, were investigated as well.

The examination is performed in order to see the situation of the roads, with different traffic characteristics, from the sample main road by ignoring traffic conditions that are rarely observed in the examination. Therefore, while benefiting from the equations in the German (R.L.S), French (G.B) and Canadian (ORNAMENTS) prediction methods and predicting the railroad noise that could be created in different conditions, the effects of the changes in the ratio of heavy vehicles, average traffic flow rate, and number of vehicles per hour were examined. As a result of this examination, Figures 1-3 were obtained.

With the values of a total of 1000 vehicles/h and 80 km/h average flow rate, the effect of the increase in the heavy vehicle ratio between the interval of 10-40%, as can be seen in Figure 1, was more influential with the Canadian noise prediction method (ORNAMENT). An increase of 25%, the effectiveness of heavy vehicle ratio would change from German method to Canadian method with the total increase of 4.8 dB(A).

With the values of total of 1000 vehicles per hour and 10% heavy vehicle ratio, the French noise prediction method was observed to be more influential in order to determine the noise that could be created for the condition of the increase in the average flow rate from 50 to 120 km/h; and thus the amount of noise would increase approximately by 4.8 dB(A) (Figure 2).

When the ratio of heavy vehicle and the flow rate were 10% and 80 km/h, respectively, the effect of the increase in the value of the total number of vehicles per hour, between the interval of 500 and 3000 vehicles, on the noise was investigated; and Figure 3 was created accordingly.

For the condition of the increase in the total number vehicles per hour from 500 and 3000, it was determined that the noise would increase approximately by 7.8 dB(A) for all of the methods (Figure 3).

As can be seen from the determinations mentioned above, the noise values predicted by using both of the methods do differ accordingly;

1. The effect of the heavy ratio on the obtained noise value is more for the German (R.L.S) method than the French (G.B) method.
2. The effect of the traffic flow speeds on the road traffic noise level orderly decreases in the French (G.B) method whereas a more out of order change is observed in the German (R.L.S) method.
3. The change of the road traffic noise levels display parallelism for both methods when the total number of vehicles increases.

According to these results, it was more or less observed for the road sections with which traffic conditions that a barrier application would be necessary according to the limit value accepted for this country. Furthermore, the noise reduction performances of the noise barrier types, of which their economical values are examined, were observed to be sufficient even for different traffic conditions investigated. In other words, there exists an implementation potential of these barriers also for other road sections with different traffic conditions.

Noise measurement implementation

A noise measurement implementation was conducted to measure the authenticity of the calculation results beside the avenue that has the previously mentioned features. The measurements were implemented from an approximately 25 m further away and 2.5 m higher than the road level. A region at the same level as the road, with no obstacles in front to prevent the noise, was chosen for this measurement. The measurements were implemented twice on the dates of 11.09.2009 and 17.09.2009, between 8:30 - 9:30 in the morning and 18:00 - 19:00 in the evening; by using SVAN 947 type sound level meter (SLM) device on 1/3 octave bands because previously presented traffic values can eventuate in these hours. A frequency weight curve was used and the calibration of the system was implemented before the measurements. SVAN ND9 type sound level calibrator, with a precision value level of ±0.3 dB, was utilized for this reason (Turkish Regulation, 2005; Turkish Standard TS 2673, 1993; Canter, 1996).

The measurement results are given in Table 4 accordingly:

1. The measurement results implemented at different times were found to be close to each other with a difference of 3-4 dB(A).
2. The values obtained from the measurement implemented in the morning were found to be a little higher than the evening values.
3. Consequently, although differences can be observed between the noise levels measured in the morning and in the evening and measurement results realized at different days, these values were considerably close to the values obtained by calculations; thus, the necessity of the noise barrier was comprehended.

Acoustic performance of noise barriers

If a noise barrier is not appropriately designed, it does not provide the desired noise protection (Kurra et al., 1984). It is essential to know the fundamental principles of acoustic barrier, in other words, how acoustic performance of noise barriers is achieved for better improved noise barrier designs. The sound spherically emanates from the source as irregular and unsteady pressure waves, yet the spherical emanation is modeled as linear lines or rays.

Barrier theory

The most significant sound transmission path on a road with no sound barriers is the direct sound ray ($L_{P,\ dir}$) between the source and receiver, as seen in Figures 4 and 5 while the other path is the ray reflected from the ground to the receiver ($L_{P,\ grd}$) (Kotzen and English, 1999). The direct ray is more effective than the reflected one. Even though the reduction mechanism is not entirely comprehended, this disparity is greater on the soft grounds, such as grass areas, and more evident around the 500 Hz frequency

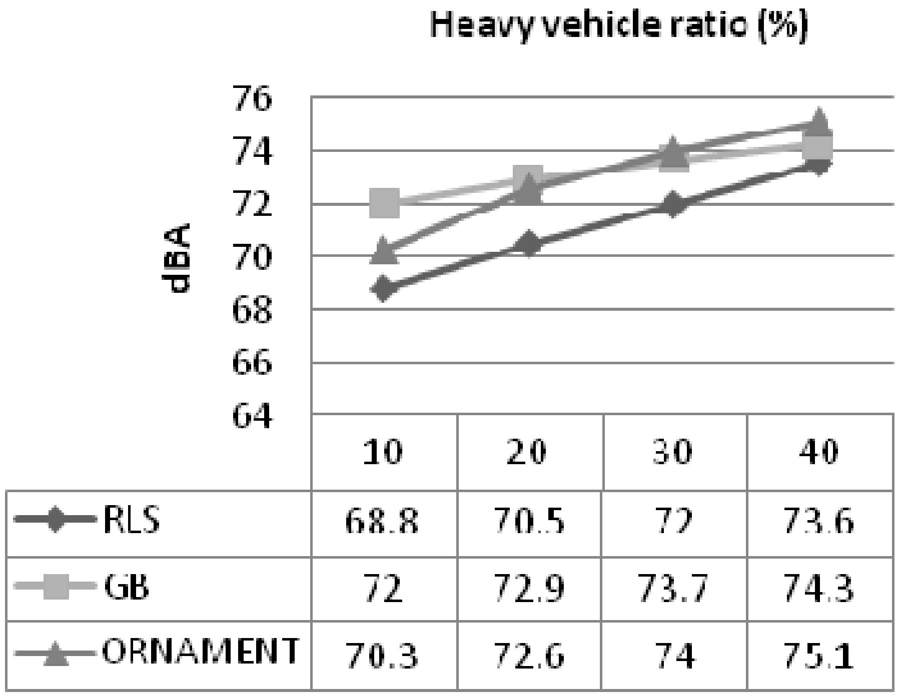


Figure 1. Noise levels in relation with the heavy vehicle ratio.

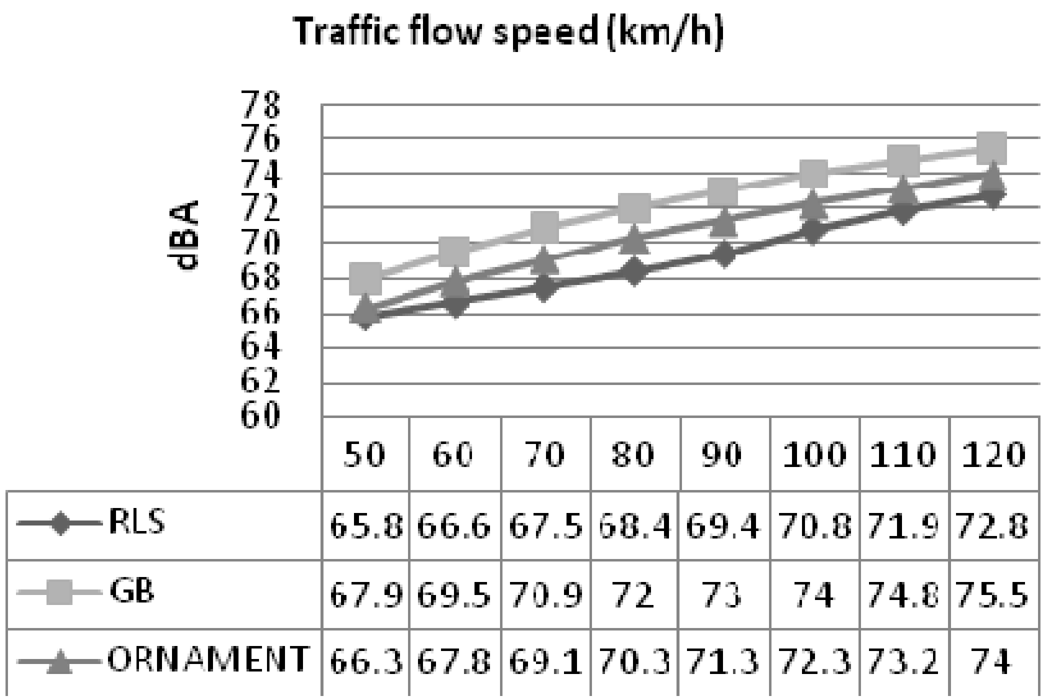


Figure 2. Noise levels that could occur for different traffic flow speeds.

level. Putting a barrier between the source and the receiver greatly decreases the strength of direct ray; nevertheless, this ray is a potential transmission path for many barriers ($L_{P,\ trans}$). Another important ray is the refractor ray that is refracted on top of the barrier ($L_{P,\ diff}$).

The barrier decreases the amount of rays reflected from the ground to a great extent. The most noteworthy study on researching the disparities between direct and refracted rays was

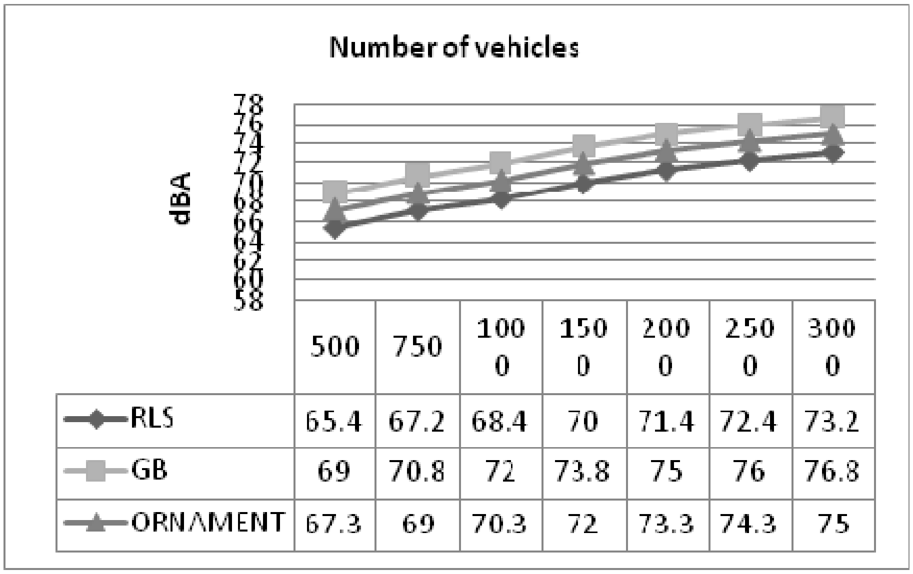


Figure 3. Noise levels that could occur for different numbers of total vehicles.

Table 4. The noise measurement results.

Measurement	Morning (08:30–09:30)	Evening (18:00–19:00)
Measurement 1	73 dB(A)	70 dB(A)
Measurement 2	74 dB(A)	71 dB(A)

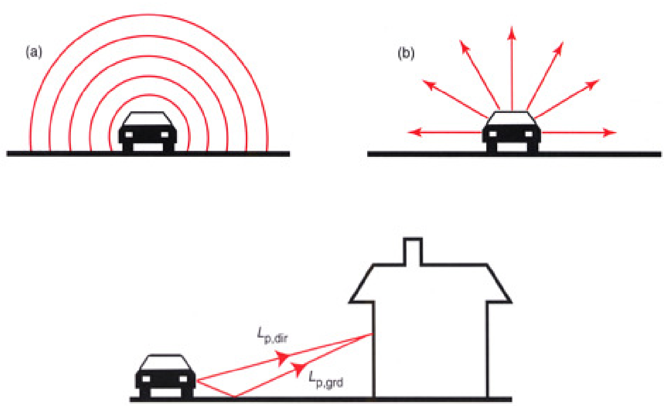


Figure 4. Unobstructed sound transmission paths (Kotzen and English, 1999).

performed by Maekawa; which involved simple and practical methods to measure the barrier performance. The developed theory computed the acoustic performance of a vertical barrier based on the Fresnel Number (N), as displayed in Equation 13 (Marsh, 1999).

$$N = 2\frac{\delta}{\lambda} \tag{13}$$

Where; δ is the distance between direct and refracted paths of sound ($L_{P,\ diff}$) - ($L_{P,\ trans}$), and λ is the wave length of sound in the air, seen in Equations 14 and 15 (Kotzen and English 1999; Kurra 1984). Sound ray paths shown in capital initials are illustrated in Figure 6.

$$L_{P,\ diff} : A+B,\quad L_{P,\ trans}: C \tag{14}$$

$$\delta: (L_{P,\ diff}) - (L_{P,\ trans}) = A + B - C \tag{15}$$

Loss due to the insertion of barrier (Insertion Loss=IL), however, can be calculated from Equations 16 and 17 (US Department of Transportation, 2006).

$$IL = 5 + 20.\log \frac{\sqrt{2\pi N}}{\tanh \sqrt{2\pi N}} \quad \text{(dB)}\ -0.2 < N < 12.5 \tag{16}$$

$$IL = 25 \quad \text{(dB)} \qquad N > 12.5 \tag{17}$$

A vehicle and its closest point were taken into account during the creation of these formulas. The diagram on Figure 7 was used for finding the traffic noise reduction value used in England. Thus, theoretical shadow zone reduction value for a barrier is 20 dB(A). On the other hand, practical reduction value limit is 15 dB(A), since required δ values are rarely achieved. When δ gets close to -0.6 m (δ≤-0.6 m) value in the illuminated zone, the reduction effect of the barrier approaches zero and some reduction is achieved in this zone; even though it is a minor one as seen in the Figure 7. δ should be greater than or equal to 0.5 m (δ≥0.5 m) to achieve reduction per 3 db(A) in the shadow zone. Composite values of N were used in the computation methods to avoid frequency based computations. They were derived from known traffic spectrums, acoustic performance of barriers, and typical composite N values corresponding to the 300-500 Hz interval. Utilizing composite values of N enables using A-weighted sound pressure levels [dB(A)] for noise reduction computations of barriers. As seen from the Equation 13, which exhibits obtainment of the Fresnel coefficient, performance of a barrier is dependent on the frequency. With the placement of barriers, medium frequency sounds in the

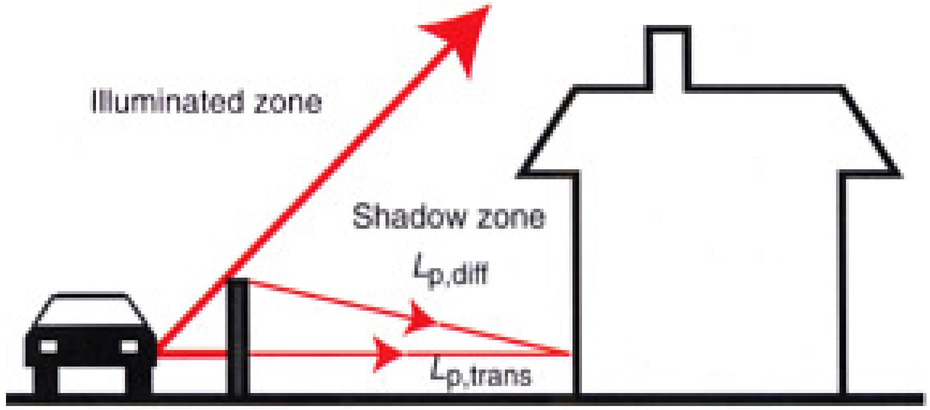


Figure 5. Key sound transmission for screened noise source (Kotzen and English, 1999).

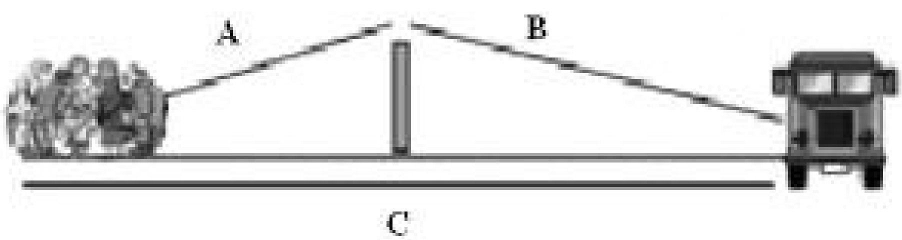


Figure 6. Sound ray paths in noise barrier.

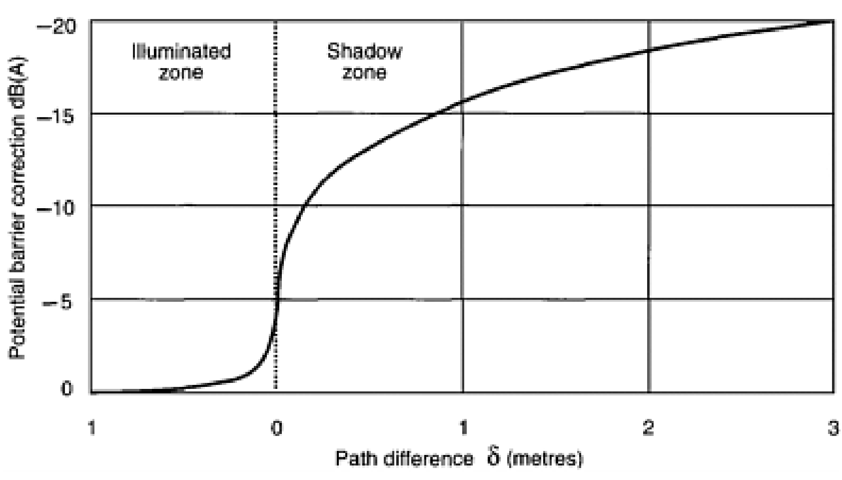


Figure 7. Potential barrier correction as a function of path difference (Kotzen and English, 1999).

receiving medium, reflecting from the ground, ($L_{P,\,grd}$) will diminish and the perceived sound will ultimately have a low frequency. If $L_{P,\,trans}$ does not have a substantial effect on the entire sound level affecting the receiver, sufficient drop off in the value of the noise can be realized by using a thin wall. A 0.5 dB(A) effect of $L_{P,\,trans}$ on the entire sound level can be considered as acceptable; therefore, the restriction in Equation 18 can be imposed (Kotzen and English, 1999).

$$L_{P,\,trans} = L_{P,\,diff} + 10 \text{ dB(A)} \quad (18)$$

The drop off provided by the noise barrier depends on many factors such as surface mass M (10 N/m^2), rigidity, and angle of sound incidence; surface mass being the most important one. United

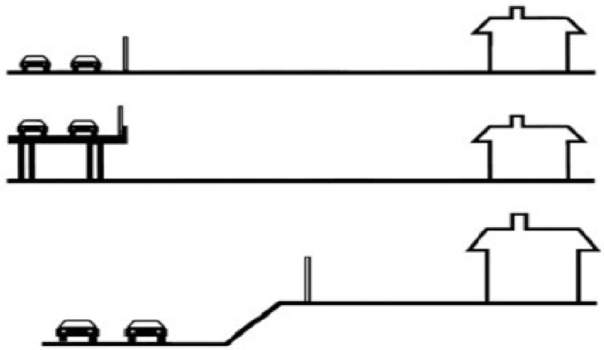


Figure 8. Placement of the barrier.

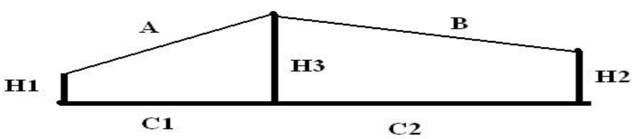


Figure 9. Distance of paths and heights of receiver-barrier and source.

Kingdom Department of Transport has been using Equation 19 for the minimum mass of the surface (Kotzen and English, 1999; Calis, 2007).

$$M = 3.10^{(\frac{A-10}{14})} \quad (10\ \mathrm{N/m^2}) \qquad (19)$$

A: potential noise drop amount dB(A) and [$A = L_{P,\,dir} - L_{P,\,diff}$]. Only the surface mass of the panel is taken into consideration here, while surface mass of materials applied to the surface and attached as a support is ignored.

Effects of barrier placement height and material selection on noise reduction level

No gaps should be present along the barrier in order to eliminate the sound leaks. The sound goes through without any reductions in wide spans; for narrow spans, on the other hand, the sound acts like a pollution source and transmits it to the other side as magnified. The barrier has to be placed as close to the source, namely the road, as possible to achieve a better performance. This situation is valid when the source and the road is on the same level or a higher elevation (on a viaduct or a bridge), as can be seen in Figure 8. In the traditional approach, the barrier should be placed considerably close to the source; the road has to be on a lower ground compared to the receiver; or there should be an elevated earth structure (for example, embankment). In this case, however, the best location for the barrier becomes the top of the inclined area (Kotzen and English, 2009).

The distance differential (δ) for each lane of the road diminishes by moving away from the barrier. Therefore, utmost effect on the receiver is caused by the furthest road lane; which affects the shape and size of the shadow area. Increasing the barrier height as a solution does not change the fact that the most dominant lane is the left lane and it causes barrier usage at an unacceptable height. In this case, it is particularly beneficial to use a second barrier and place it between the lanes of a two-way road. Thus, lanes on both directions are considered as different sources while both barriers will be placed closest to both sources. This technique not only lowers the barrier height but also provides significant noise reduction with the aid of substantially wide roads with plenty of lanes for the cases where the receiver is above the road elevation. It is not possible to have the receiver and source on the same plane for the buildings at elevations higher than the road because sloping, which will occur due to elevation difference, plays the role of a barrier and causes reflection or diminishing of the noise (Demirel, 1996; Mc Clellan et al., 2006).

Notations in Figure 9 represent the following; H_1 the height of the source from the ground level, H_2 the height of the receiver from the ground level, H_3 the height of the barrier, C_1 distance between the source and the barrier, C_2 the distance between the receiver and the barrier, A the distance between the vertexes of the source and the barrier, B the distance between the vertexes of the receiver and barrier.

Fluctuation of the noise amount, which will be perceived by the receiver depending on the location of the panel, will be investigated to analyze the noise reduction depending on the location of the barrier when there is a constant noise source. Road platform widths in Istanbul usually change from 10 to 13 m on the main and secondary roads, respectively, while they stay between 7.5 and 8 m on the ancillary roads. Formulas used for the noise production of a known traffic conditions and noise reduction of a noise barrier was given previously. The frequency of traffic noise and distance of the receiver to the road were selected as 500 Hz and 27 m, respectively, in all computations while the noise reduction amounts (IL-Insertion Loss–Noise loss due to the insertion of the barrier) were analyzed based on the previously given formulas and conditions.

Effect of barrier distance to the source

Noise reduction amounts were analyzed for three different scenarios to study the effect of barrier distance to the source. These scenarios are: barrier close to the noise source, in the middle of the source and the receiver, and close to the receiver.

Barrier close to the source

For the scenario where the barrier is close to the source; five different values (1, 2, 3, 4 and 5 m) were used as the distance of the noise barrier to the road (C_1); and the noise reduction performances for each distance are presented in Table 5. When the distance was raised from 1 to 5 m, reduction effect of the barrier displayed approximately variation of 4 dB(A); in other words, 4 dB(A) more noise reduction was gained when a barrier is placed at 1 m away from the source when compared to the same barrier at 5 m distance.

Barrier in the middle of source and receiver

A 3 m barrier was placed at different displacements to analyze the scenario where the barrier is in the middle of the source; and then the receiver and the effect of displacement change on the noise reduction was studied accordingly. The reduction values obtained from these calculations are given in Table 6. According to the values in Table 6, noise reduction performance first decreases and then increases again when the barrier moves away from the noise source. When the barrier is 6 m away from the source, on the other hand, the reduction was 15.44 dB(A). This value dropped to 13.47 dB(A) at 15 m and moved up to 14.46 dB(A) at 21 m.

Table 5. Performance of barrier close to the source.

A (m)	B (m)	C_1 (m)	C_2 (m)	H_1 (m)	H_2 (m)	H_3 (m)	δ (m)	N	I L dB(A)
2.69	26.08	1	26	0.5	1	3	1.76	5.20	20.15
3.20	25.08	2	25	0.5	1	3	1.28	3.77	18.75
3.91	25.08	3	24	0.5	1	3	0.99	2.91	17.62
4.72	23.09	4	23	0.5	1	3	0.80	2.36	16.73
5.59	22.09	5	22	0.5	1	3	0.68	2.00	16.01

Table 6. Performance of barrier in the middle of source and receiver.

A (m)	B (m)	C_1 (m)	C_2 (m)	H_1 (m)	H_2 (m)	H_3 (m)	δ (m)	N	I L dB(A)
6.50	21.10	6	21	0.5	1	3	0.60	1.75	15.44
7.43	20.10	7	20	0.5	1	3	0.53	1.57	14.97
8.38	19.10	8	19	0.5	1	3	0.49	1.43	14.58
9.34	18.11	9	18	0.5	1	3	0.45	1.33	14.27
10.31	17.12	10	17	0.5	1	3	0.43	1.25	14.01
11.28	16.12	11	16	0.5	1	3	0.41	1.19	13.81
12.26	15.13	12	15	0.5	1	3	0.39	1.15	13.66
13.24	14.14	13	14	0.5	1	3	0.38	1.12	13.56
13.73	13.65	13.5	13.5	0.5	1	3	0.38	1.11	13.52
14.22	13.15	14	13	0.5	1	3	0.37	1.10	13.49
15.21	12.17	15	12	0.5	1	3	0.37	1.10	13.47
16.19	11.18	16	11	0.5	1	3	0.37	1.10	13.49
17.18	10.20	17	10	0.5	1	3	0.38	1.12	13.56
18.17	9.22	18	9	0.5	1	3	0.39	1.15	13.68
19.16	8.25	19	8	0.5	1	3	0.41	1.21	13.87
20.16	7.28	20	7	0.5	1	3	0.44	1.28	14.12
21.15	6.32	21	6	0.5	1	3	0.47	1.39	14.46

Table 7. Performance of barrier closer to the receiver.

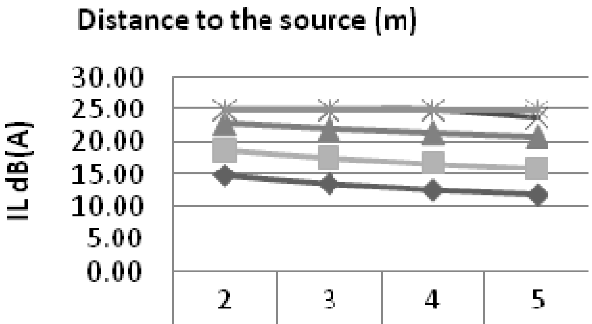
A (m)	B (m)	C_1 (m)	C_2 (m)	H_1 (m)	H_2 (m)	H_3 (m)	δ (m)	N	I L dB(A)
22.14	5.39	22	5	0.5	1	3	0.53	1.55	14.92
23.14	4.47	23	4	0.5	1	3	0.61	1.79	15.52
24.13	3.61	24	3	0.5	1	3	0.74	2.16	16.34
25.12	2.83	25	2	0.5	1	3	0.95	2.80	17.46
26.12	2.24	26	1	0.5	1	3	1.36	3.99	18.99

Barrier close to the receiver

The effect of placing the barrier close to the receiver on the noise reduction performance was studied; and the results of reducing the distance from 5 to 1 m are presented in Table 7. When the barrier approached the receiver, a 4 dB (A) increase in the noise reduction performance occurred for this example. Nonetheless, it is observed that the noise reduction amounts were not symmetrical with respect to the barrier distance. The noise reduction amount of a barrier 1 m close to the source was found to be greater than a barrier 1 m close to the receiver. Results in Table 7 are also consistent with the logic of “barrier close to the source grants greater noise reduction” (Hong Kong EPG, 2006; Ozturk, 1992).

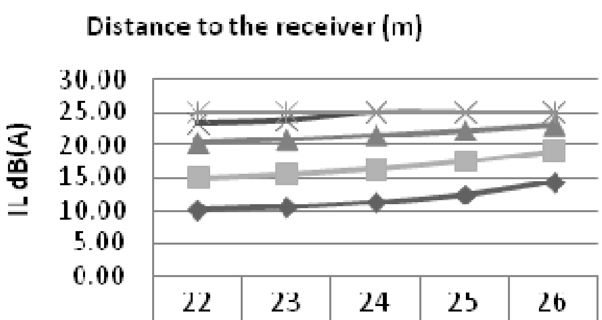
The effect of barrier height

When the effect of barrier height on noise reduction performance of



	2	3	4	5
2 m bariyer	14.86	13.50	12.51	11.77
3 m bariyer	18.75	17.62	16.73	16.01
5 m bariyer	22.78	22.04	21.41	20.86
7 m Bariyer	25.00	25.00	25.00	23.69
10 M Bariyer	25.00	25.00	25.00	25.00

Figure 10. Relationship between (IL) and height of barrier close to the source.



	22	23	24	25	26
2 m Barrier	10.05	10.51	11.21	12.34	14.32
3 m Barrier	14.92	15.52	16.34	17.46	18.99
5 m Barrier	20.36	20.87	21.50	22.25	23.12
7 m Barrier	23.41	23.81	25.00	25.00	25.00
10 m Barrier	25.00	25.00	25.00	25.00	25.00

Figure 11. Relationship between (IL) and barrier height close to the receiver.

the barrier was examined, barrier heights at areas close to the receiver and the source, which are the critical lengths of the graph in Figure 9, were used.

Assessment of height of the barrier closer to source

The value of noise reduction due to barrier height change was examined as a result of placing the barrier at distances that vary between 2-5 m away from the source in this section. The effect of 4 different barrier heights (2, 3, 5 and 7 m) on the noise reduction was studied for each assessed distance. When the barrier was placed within the first 4 m, a reduction effect, which can be theoretically obtained by a 7 m tall barrier, occurred; and an excellent performance that reached the maximum noise reduction value of 25 dB(A) was achieved. Nevertheless, a 7 m barrier height becomes insufficient when the distance was equal to or greater than 5 m; so, the barrier height needs to be raised to 10 m to obtain a full noise reduction. The results are displayed in Figure 10.

Assessment of barrier height close to receiver

The change in the noise reduction value due to barrier height change was examined as a result of placing the barrier 22-26 m away from the source and close to the receiver in this section. Reduction values for 5 different barrier heights (2, 3, 5, 7 and 10 m) were calculated for each distance; where C_1 and C_2 varied between 22 and 26 m, and 5 and 1 m, respectively. It was observed, as a result, that the closer the barrier is to the receiver, the more increase in the noise reduction effect. For example, a 3 m tall barrier gained 18.99 dB(A) noise reduction when it was 1 m away from the receiver whereas when this distance was 5 m, 14.92 dB(A) reduction was gained. Furthermore, when barriers taller than 7 m ($H_3 \geq 7$ m) were placed 3 m away from the source, barrier performance peaked as a reduction value of 25 dB(A). These results are displayed in Figure 11.

For decision makers, reasonable pricing in construction costs is the first and best solution to choose between the options of different construction types. In construction of noise barriers, the height and material which are determined according to traffic variables affect the total cost. Moreover, since the unit price of each construction element and labor cost differ from one country to another depending on the economical conditions, the construction costs of different types of noise barriers differs as well. In this study, Canadian and Turkish costs of noise barrier construction are analyzed for two different types of noise barriers with two different heights.

Assessment of construction costs of noise barriers

The cost of noise barrier is associated with the material used and performance of the barrier. According to Equation 19, while selecting the barrier material, first surface mass of the materials that will provide a specific transition loss (TL) is determined, and then the material suitable for transition loss is selected from them, as displayed in Table 8 (Hong Kong EPD, 2003; Fleming et.al., 2000).

Based on the noise barrier design guide published on Hong Kong Environment Protection Department website, transition loss value of a material to be used for noise barriers should be 10 dB(A) more than the required noise reduction value, or namely insertion loss (IL). For example, if the required reduction value of a barrier is 8 dB(A), then the TL value of the material to be used for this barrier should be at least 18 dB(A). The logic behind this adjustment is that the noise value (L_{diff}) generated by refracted sound rays is at least 10 dB(A) more than the TL value (Wu, 1999).

Since maximum reduction value that can be obtained from noise barriers is 25 dB(A), selecting a material that has a TL value above 35 dB(A) would satisfy any kind of condition.

Barrier material and costs

Change and thickness in the surface mass of the material will not alter the TL level significantly. Even though the usage of a material with a surface mass of 100 N/m^2 would be sufficient for general purpose usage and any kind of condition, it is suggested that this value should be calculated again for each project. Surface mass

Table 8. Transmission loss (TL) of various materials based on barrier surface mass.

Material	Thickness (mm)	Surface density (kg/m^2)	Transmission loss dB(A)*	Transmission loss dB(A)**
Polycarbonate	8-12	10-14	30-33	-
Acrylic [Poly-Methyl-Meta-Acrylate (PMMA)]	15	18	32	-
Concrete block 200x200x400 light weight	200	151	34	34
Dense concrete	100	244	40	40
Light concrete	150	244	39	39
Light concrete	100	161	36	36
Brick	150	288	40	-
Steel, 18 gal	1.27	9.8	25	25
Steel, 20 gal	0.95	7.3	22	22
Steel, 22 gal	0.79	6.1	20	20
Steel, 24 gal	0.64	4.9	18	18
Aluminum sheet	1.59	4.4	23	23
Aluminum sheet	3.18	8.8	25	25
Aluminum sheet	6.35	17.1	27	27
Wood	50	32.7	-	24
Wood	25	18	21	21
Wood	12	8.3	-	18
Plywood	13	8.3	20	20
Plywood	25	16.1	23	23
Absorptive panels with polyester film backed by metal sheet	50-125	20-30	30-47	-
Glass, Safety	3.18	7.8	-	22
Plexiglass	6	7.3	-	22

* Hong Kong EPD (EPD Guideline, 2003), ** FHWA (Fleming et al., 2000).

values of barrier materials for different IL levels, which were calculated according to Equation 19, are presented in Table 9. Based on these values, appropriate materials were selected from Tables 8 and 9, (FHWA, 2006).

Construction cost research of noise barriers were founded on the metric length of noise barriers according to the conditions in Turkey. Required IL was determined for reducing the noise value, calculated according to the previously given road and traffic values, to the desired level. Materials were selected for four different heights and IL levels obtained before; and construction cost of the noise barrier was determined accordingly.

Four different values (1, 3, 5 and 7 m) for the distance of barrier to the road and three different values (3, 5 and 7 m) of barrier heights were used; and then noise reduction amounts obtained for different surface mass values were analyzed accordingly. 60 dB(A), as the noise limit for the areas sensitive to the noise as given in Noise Control Regulation, was used in this study. Consequently, a reduction value of 16.7 dB(A) is required, hence the expected traffic-sourced noise level was determined to be 76.7 dB(A).

In Table 10, the distance of barrier to the road and barrier height values were taken as 1, 3, 5, and 7 m and 3, 5 and 7 m, respectively. According to the results, it is observed that a 3 m tall barrier would not provide the desired noise level in the receiving medium under these conditions whereas 5 and 7 m tall barriers would be adequate for the required reduction. As stated previously, noise reduction performance of a barrier is defined not by the surface mass of barrier material but its height and relevant distances. Case 1 was the basis for the cost analysis and materials selected accordingly are given in Table 11.

For the given barrier heights and material types, unit prices and total costs of barriers were calculated for the conditions in Turkey; and the results are presented in Table 11. The construction costs of noise barriers were computed using 2009 unit prices published by The Ministry of Public Works and Settlement (Turkish Unite Price, 2009) while market prices were used for the materials not listed in this document (it was assumed that 1 Canadian $=1.4 TL for the year of 2009).

To make a comparison of Turkish and Canadian construction costs of noise barriers, approximate unit costs of building concrete and plywood walls were considered for the state of Ontario (Home improvement costs, 2010). For the concrete noise barrier, unit cost is taken as 300-350 CAD/m^2 and for the plywood noise barrier; unit cost is taken as 200-250 CAD/m^2. The comparison of construction costs of noise barriers is simply shown in Table 12.

Barrier costs vary depending on the material and labor costs. The metric costs of barriers made of concrete and plywood, which is recently being preferred for barrier applications in Turkey, was studied with using 5 and 7 m height samples. When all cost components associated with barrier application were analyzed with using two barriers at the same height but made of different materials, it was found that plywood barriers were noticeably more expensive than the concrete ones. The reason for this difference in construction costs can be attributed to the high cost of standard plywood, which is not covered with a waterproof film, compared to the low cost of concrete. Various concrete noise barrier construction costs for 1 km are given in Table 14 (Reynolds, 1992) and costs of

Table 9. Best fit material according to surface mass and TL.

IL dB(A)	TL dB(A)	Surface mass ($10N/m^2$)	Best fit material
2	12	0.8	1.59 mm aluminum
4	14	1.1	1.59 mm aluminum
6	16	1.6	1.59 mm aluminum
8	18	2.2	1.59 mm aluminum
10	20	3.0	1.59 mm aluminum
12	22	4.2	1.59 mm aluminum
14	24	5.8	0.8 mm steel
16	26	8.0	3.18 mm aluminum 13 mm plywood
18	28	11.2	8-12 mm poly-carbonate
20	30	15.5	25 mm plywood 6.35 mm aluminum Metal back, polyester film covered, noise absorbing panel
22	32	21.6	All concrete types Brick Metal back, polyester film covered, noise absorbing panel
24	34	30.0	All concrete types Brick Metal back, polyester film covered, noise absorbing panel
25	35	35.4	All concrete types Brick

Table 10. Case study of material-height-distance of barrier and IL.

Variable	Unit	Height (m)	Case 1	Case 2	Case 3	Case 4
Barrier distance to the road	(m)		1	3	5	7
Noise level	dB(A)		76.7	76.7	76.7	76.7
Noise level limit	dB(A)		60	60	60	60
Necessary IL	dB(A)		16.70	16.70	16.70	16.70
Extended IL	dB(A)	3	14.74	13.63	12.78	12.10
Surface mass of material	$10\ N/m^2$	3	6.54	5.45	4.74	4.24
Extended IL	dB(A)	5	19.79	18.87	18.17	17.62
Surface mass of material	$10\ N/m^2$	5	15.01	12.91	11.49	10.51
Extended IL	dB(A)	7	22.80	22.08	21.52	21.09
Surface mass of material	$10\ N/m^2$	7	24.65	21.88	19.94	18.60

other noise barrier types are given in Table 15 (OECD, 1995).

RESULTS

This study analyzed national construction costs and noise reduction performance of the barriers, based on variables such as distance and height, and drew several important conclusions. These are as follows:

1. Noise reduction effect increases when the barrier is close to the road. An additional 4 dB(A) reduction was gained with a barrier 1 m away from the road compared to the same barrier at 5 m distance.
2. When the barrier moves away from the noise source, noise reduction performance first decreases then increases again. For example, if the barrier is 6 m away from the noise source, reduction performance was measured as 15.44 dB(A). This value dropped to 13.47

Table 11. Selection of barrier material according to variables.

Variable	Unit	Height (m)	Case 1	Best fit material
Extended IL	dB(A)	5	19.79	-155 N/m^2 -25 mm plywood -6.35 mm aluminum - Metal back, polyester film covered, noise absorbing panel
Surface mass of material	N/m^2	5	150.1	
Extended IL	dB(A)	7	22.80	-216 N/m^2 - All concrete types - Brick -Metal back, polyester film covered, noise absorbing panel

dB(A) at 15 m distance, and raised back to 14.46 dB(A) at 21 m distance.

3. When the barrier approaches the receiver, approximately 4 dB(A) increase in noise reduction performance was observed. Nevertheless, it was observed that noise reduction amounts were not symmetrical to the barrier distance. Noise reduction amount of a barrier 1 m away from the source is more than the noise reduction amount of a barrier 1 m away from the receiver.
4. The effect of barrier surface mass on the noise reduction was also studied; and barriers with various heights (3, 5 and 7 m) were placed at various distances to the road (1, 3, 5 and 7 m).

DISCUSSION

Considering Turkish and Canadian approximate market prices, metric costs of 7 and 5 m barriers were analyzed. Results in Tables 12 and 13 show that there is a significant difference between the costs of two materials with the same height, but made of different material type. It was also observed that a concrete barrier is cheaper than a plywood barrier in Turkey and vice versa for the Canada.

The main reason for this cost difference between Turkey and Canada is that, Canada has a big amount of woodland (approximately 48% of total land) and the wooden products are considerable cheaper than Turkey. Table 13 shows that concrete noise barrier costs are nearly the same for both of the countries. This small difference may be as a result of labor cost.

For Turkey, major items that affect the construction cost of concrete barriers are concrete forms made of plywood again. Depending on the workload, steel forms are being used to decrease the cost. Even though the financial cost is high, it is more advantageous in large volume work considering the strength of steel forms.

When advantages such as labor and lack of detailed work during the construction of noise barriers, durability, operation life, and expertise in concrete construction in Turkey are considered in addition to economy, the preference of concrete barrier looks like the right decision, (Ozturk, 1992, 1994).

Conclusions

A short examination was conducted given details in the introduction part of the study. By utilizing the Turkish/French, German and Canadian noise prediction methods, the effects of the conditions of the change in the heavy vehicle ratio, average traffic flow, and hourly total vehicle number on the noise and curtain need were investigated.

All calculated or observed results showed that noise barrier construction was necessary and 3 m tall barrier could not perform the desired noise reduction at all distances while 5 and 7 m tall barriers could. It was concluded that the actual noise reduction performance is not defined by the surface mass of used material but by the height of the barrier and the related distances.

Factors such as cost, aesthetics, and durability influence the selection of material type if the noise reduction amounts of two barriers, which have the same height and reduction properties but made of different materials, are equal, recycled materials should be preferred to get economic solutions for noise barrier construction. Particularly, materials such as plastic and PVC are durable as well as being economical. The metric cost of the noise curtain is expected to be in relation with the per capita income of that country because as the per capita income increases, an increase especially in the labor and engineering services is observed.

Noise barrier construction, even it is not the most economical solution, must be installed at areas sensitive to noise, such as hospitals and schools, regardless of

Table 12. Construction costs of various types and heights of barriers.

Work type	7 m reinforced concrete unit	7 m plywood unit	5 m reinforced concrete unit	5 m plywood unit	Unit	Unit Cost (CAD)	7 m reinforced concrete CAD/m	7 m plywood CAD/m	5 m reinforced concrete CAD/m	5 m plywood CAD/m
Digging cost of topsoil by hand	500	50	500	50	m^3	6.9	3.5	0.3	3.5	0.3
Truck hauling of excavated soil out of site	10000	500	10000	500	kN	6.5	6.5	0.3	6.5	0.3
Wire mesh carriage	350	-	250	-	kN	7.9	0.3	-	0.2	-
Wire mesh (formed) (TS 4559- 30.0-100.0 N/m^2)	350	-	250	-	kN	0.5	16.8	-	12.0	-
Placement of formed wire mesh (30.0-100.0 N/m^2)	350	-	250	-	kN	800.5	28.0	-	20.0	-
Carriage of any type of reinforcement profile iron	55	170	55	120	kN	50.0	0.3	0.9	0.3	0.6
Reinforcement, formed (BÇIIIa), (BÇIVa), Ø8-12 mm	55	-	55	-	kN	378.6	2.1	-	2.1	-
Bending and placement of reinforced Ø8-12 mm	55	-	55	-	kN	798.2	4.4	-	4.4	-
Smooth surface plywood (film covered) form	14000	-	10000	-	m^2	11.6	162.9	-	116.4	-
Carriage of ready mix concrete	1900	50	1500	50	m^3	9.9	18.8	0.5	14.9	0.5
C16/20 concrete, including pumping	1900	50	1500	50	m^3	56.8	151	2.8	85.0	2.8
Opening Anchorage Reinforcement Holes in 0-20 m (20 m included) deep in any angle and in any type of soil	-	32	-	32	m	22.8	-	0.7	-	0.7
Anchorage reinforcement12 Ø8	-	135	-	135	Piece	9.5	-	1.3	-	1.3
25 mm waterproof plywood (250x125x2.5 cm)	-	2240	-	1600	Piece	160.7	-	360.0	-	257.1
NPI 80 profile Iron	-	167.02	-	119.3	kN	0.8	-	13.1	-	9.4
Stainless steel sheet (8000 N/m^3-2x1500x3000 cm)	-	4010	-	4010	N	1.4	-	0.6	-	0.6
Total ($/m)							351.3	380.2	265.2	273.7

Table 13. Noise barrier construction cost comparison (Turkish versus Canadian).

Variable	Canada ($/m)	Turkey ($/m)
7 m reinforced concrete	350	350
5 m reinforced concrete	300	265
7 m plywood	250	380
5 m plywood	200	275

cost, as a social responsibility. Emphasizing on the environmental problems and increasing the awareness towards noise within this context in developing countries, as in Turkey; and an increase in constructing solutions to prevent noise accordingly would be a sign of development and

Table 14. Contruction cost of concrete noise barrier.

Option	Height (m)	Cost ($/km)
Concrete noise barrier	1	106000
	2	212000
	3	319000

Table 15. Noise barrier costs.

Type of noise barrier	Cost per square meter (US Dollar)
Concrete	75-300
Wood	60-260 (430 for absorptive)
Aluminum or steel (metal)	110-240
Metilmet acrylic or polycarbonate (transparent)	250-470
Green or vegetative (bio-walls)	240-270
Concrete with New Jersey base	125-220
Eco-technique barrier for viaduct	190-215

modernity.

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