AGRICULTURAL UNIVERSITY - PLOVDIV
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Typology and Methods for Noise Abatement Using Urban Green Infrastructure

ABSTRACT

of a dissertation for the award of the Educational and Scientific Degree "Doctor"

Scientific Specialty: Ornamental Plants

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The dissertation is 210 pages long and contains 29 tables and 30 figures. The list of references includes 157 sources, 35 of which are in Cyrillic and 122 in Latin script.

The experimental research was conducted within the Sofia metropolitan area (covering 19 systematic permanent control points and additional specialized locations within the framework of specific project case studies) throughout the doctoral candidature period.

The dissertation has been reviewed and approved for defense by the Department Council of the Department of Horticulture, Faculty of Viticulture and Horticulture at the Agricultural University – Plovdiv.

The public defense of the dissertation will take place on [Date] 2026, at [Time], in [Hall Name], Faculty of Viticulture and Horticulture, Agricultural University – Plovdiv, before the Specialized Scientific Jury appointed by the Rector of the Agricultural University under Order No. [Number] of 2026, composed of:

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The dissertation materials are available for review on the website of the Agricultural University – Plovdiv – www.au-plovdiv.bg

1.INTRODUCTION AND RELEVANCE OF THE PROBLEM

The sustainable development of the modern city is an exceptionally complex, multi-layered task that has long transcended the scope of traditional engineering planning. Its ultimate goal is to maintain the ecological balance of our habitats and to protect the citizens' right to a favorable and healthy living environment. However, the pursuit of intensive economic growth, urban development, and mobility in large agglomerations generates one of the most aggressive and pervasive pollutants in contemporary society – anthropogenic traffic noise.

Acoustic discomfort in urban areas has long ceased to be merely an annoying inconvenience or a local aesthetic issue. According to categorical data from the World Health Organization (WHO) and numerous epidemiological studies, noise functions as a potent chronic stressor – an "invisible enemy" that causes lasting, cumulative damage to the physical and mental health of the population, increasing the risk of cardiovascular diseases, cognitive deficits, and sleep disorders.

Traditional urban planning relies primarily on conventional "hard" engineering measures, such as the construction of massive concrete or polycarbonate noise barriers. While these structures possess proven acoustic efficiency, they often act as "foreign bodies" within the urban fabric, disrupting visual axes, impeding natural ventilation, and creating a sense of social isolation for the adjacent territories. In this context, the vast, yet still insufficiently researched and systematized potential of green infrastructure, and more specifically of green noise-reducing phyto-screens, becomes apparent.

Unlike artificial engineering barriers, a vegetation belt does not merely reflect sound waves. It acts as a complex biological system that transforms sound energy through a synergy of physical processes – absorption by the porous structure of the biomass and soil, diffraction around plant canopies, and multiple internal scattering. Simultaneously, phyto-screens provide irreplaceable ecosystem services: they purify air masses from particulate matter (PM) and gaseous emissions, mitigate the urban heat island effect, and enrich the landscape environment. In Bulgaria, and specifically regarding the conditions of the Sofia agglomeration, there is a lack of a comprehensive, scientifically validated applied toolkit that links the dendrological composition and spatial architectonics of plantings with specific quantitative calculations of the attenuation effect. This dissertation thesis aims to bridge this significant scientific and applied gap.

2. AIM, OBJECTIVES, AND WORKING HYPOTHESIS

Aim of the Research: The aim of this dissertation is to develop a scientifically grounded concept comprising spatial-functional typological models and methodological guidelines for the design of high-efficiency green noise-reducing screens. Furthermore, the aim is to quantify the phyto-acoustic potential of a specific reference assortment of tree and shrub species within the real-world ecological conditions of the Sofia metropolitan area.

Objectives of the Research:

1. Systematization and detailed analysis of the physico-biological mechanisms of propagation, absorption, and scattering of sound waves through vegetation arrays.
2. Conducting systematic *in situ* instrumental monitoring at selected control points along the primary street network of Sofia.
3. Experimental determination and quantitative measurement of the influence of the seasonal factor (phenological phases of foliage and dormancy) on the insulation capacity of broad-leaved and coniferous belts.
4. Execution of a multi-criteria dendrological analysis and assessment of the ecological plasticity and gas resistance of priority species under conditions of anthropogenic stress.

5. Development of digital phyto-acoustic models and the creation of an original Constructive Typology of phyto-screens (Type 1, Type 2, and Type 3) for practical application.

Working Hypothesis: The research is based on the scientific hypothesis that the acoustic efficiency of vegetation barriers is not a simple linear function of the total biomass quantity; rather, it exists in a non-linear relationship with the internal structural organization of the plantation (vertical stratification, density, micro-morphology), its distance from the noise source, and seasonal phenological dynamics. It is posited that properly constructed multi-story phyto-screens can provide acoustic protection fully comparable to that of conventional technical barriers.

3. OBJECT, SUBJECT, AND RESEARCH METHODOLOGY

3.1. Object and Subject of the Research

The **object** of this research is the urban environment of the Sofia metropolitan area. The experimental and analytical foundation of the dissertation encompasses two parallel streams of empirical data:

- **Systematic monitoring network:** Comprising 19 permanent control points situated along the primary street network (urban highways and boulevards), which define the general noise climate of the capital city.
- **Specific project locations:** Covering concrete experimental and verified real-world sites (e.g., the linear park on "Makedonia" Blvd., "Nikola Vaptsarov" Blvd., "Zelin" residential area in Botevgrad, and the "Technopolis" commercial complex), where specialized series of acoustic measurements were conducted for the purposes of spatial modeling and evaluating the actual efficiency of the phyto-screens.

The **subject** of the research encompasses the levels of anthropogenic acoustic load generated by vehicular traffic and the structural-morphological parameters of the adjacent tree and shrub vegetation.

3.2. Research Material and Ecological Selection

The research material encompasses the existing tree and shrub vegetation utilized to form linear protective structures. Within the framework of the study, the selection of target dendrological material is strictly aligned with the specifics of the temperate continental climate, local soil conditions, and the orography of the Sofia Basin (frequent temperature inversions, summer droughts, and high levels of anthropogenic stress).

To ensure the long-term efficiency of the constructed protective structures, the species have been classified based on their ecological plasticity (Table 1):

- **Adaptability to urban stress:** Priority has been given to taxa capable of tolerating heavy soil sealing, compaction, and winter salinization (e.g., *Robinia pseudoacacia* and *Acer negundo*).
- **Temporal screening dynamics:** Fast-growing pioneer species (*Populus x canadensis*) have been integrated to achieve early protection within shortened timeframes (3–5 years), combined with long-lived climax species (*Quercus robur*) to form a sustainable framework.
- **Phenological dynamics:** The timing of leaf emergence and abscission is a determining factor. It is mandatory to include evergreen taxa (*Picea abies*, *Pinus nigra*), which serve as an acoustic buffer during the winter period, when sound propagation is most intense due to temperature inversions.

3.3. Indicators, Criteria, and Research Methodology

For the purpose of this dissertation, a comprehensive research methodology has been developed and applied, integrating quantitative (precise instrumental measurements) and qualitative (expert-analytical) approaches. The core conceptual framework is designed as a comparative seasonal analysis.

3.3.1. Instrumentation and Technical Specifications

In situ instrumental acoustic monitoring was conducted using a specialized digital sound level meter (Model SL300), complying with the international standard for electroacoustics DIN EN 61672-1 (Class 2). The choice of this portable device was dictated by the requirements for mobility and durability against dust and vibrations in a harsh urban environment. The permissible error of ±1.4 dB(A) fully satisfies the requirements for expert monitoring and comparative analysis.

Operating parameters of the measurement system:

- **Frequency range:** 31.5 Hz – 8 kHz. This range effectively covers both low-frequency emissions (from engines) and high-frequency aerodynamic noise (from tire-road interaction).
- **Time constants:** The "FAST" mode (125 ms) was used for precise identification of short-duration noise transients from individual vehicles, while the "SLOW" mode (1 s) was employed to calculate stable equivalent noise levels (L_{Aeq}) of the overall traffic flow.

3.3.2. Combined Method of Expert Assessment

Beyond instrumental recording, the methodology integrates a multi-criteria analysis of the biological factor and the physical environment:

1. **Dendrological expertise:** Conducted on-site to assess biological status, canopy architecture (presence of "acoustic gaps" in the understory), and the structural origin of the plantation.
2. **Assessment of environmental conditions:** Includes an infrastructure audit of the road surface and local topography (presence of reflecting facades). Acoustic measurements were conducted under strictly controlled abiotic conditions: dry road surface, no precipitation, relative humidity below 90%, and wind speed below 5 m/s, to eliminate wave refraction.

3.3.3. Field Measurement Algorithm

Field measurements were conducted using a two-stage linear model, allowing for the direct calculation of the barrier's actual insulation capacity, defined as Insertion Loss (IL). The microphone was positioned at a height of 1.2 to 1.5 meters above ground level.

- **Stage 1: Measurement at the source (Emission Point):** Conducted at the edge of the carriageway to establish the "raw" emission. Measurements were performed in two time windows:
  - **Morning peak hour (08:00 – 08:30):** To record extreme acoustic load.
  - **Afternoon off-peak period (14:00 – 14:30):** To record the base working background level.
- **Stage 2: Measurement behind the protective barrier (Immission Point):** Conducted at a standardized distance of 15 meters from the source, in the geometric center behind the vegetation belt.
- **Seasonal indicator:** Measurements were repeated under identical topological conditions in summer (maximum foliage) and winter (defoliated structure), allowing for the precise calculation of the seasonal loss of acoustic efficiency.

Table 1.

Acoustic and Aeration Parameters of the Investigated Material

Model Parameter	High-Performance Species	Acoustic and Ecological Impact
High canopy density	*Picea abies*, *Thuja occidentalis*, *Acer platanoides*	Maximum absorption of the high-frequency noise spectrum and intensive particulate matter retention.
High porosity (Permeability)	*Betula pendula*, *Fraxinus excelsior*, *Gleditsia triacanthos*	Enhances vertical air mass transfer, ensures aeration, and prevents gaseous stagnation.

Developed root system	*Robinia pseudoacacia*, *Acer campestre*	Provides increased mechanical stability; crucial for reinforcing roadside slopes.
Leaf micro-morphology (Trichomes)	*Tilia tomentosa*	Optimizes Specific Leaf Area (SLA); trichomes act as micro-traps for capturing PM (particulate matter).
Seasonal permanence (Evergreen habit)	× *Cupressocyparis leylandii*, *Taxus baccata*	Eliminates the seasonal collapse of the barrier's efficiency; ensures consistent acoustic impedance.
Pruning tolerance (Basal compactness)	*Ligustrum vulgare*, *Prunus laurocerasus*	Allows for the formation of dense structures in confined spaces; seals "acoustic windows."

3.3. Research Methodology, Indicators, and Criteria

To ensure high scientific reliability, a complex methodology was applied, incorporating *in situ* instrumental acoustic monitoring using a precision digital sound level meter (Model SL300, compliant with IEC 61672 Class 2 standards), combined with a comparative seasonal analysis (the period of full foliage in summer versus the period of biological dormancy and defoliation during winter months). The instrumentation operates within a frequency range of 31.5 Hz – 8 kHz, fully covering both low-frequency engine emissions and high-frequency aerodynamic noise, utilizing "FAST" (125 ms) and "SLOW" (1 s) time constants.

The selection of the 19 measurement locations was strictly based on the level of acoustic load (zones exceeding 65–75 dB(A)), the functional zoning (residential, public service, and mixed-use areas), and the available dendrological diversity at the specific sites (Table 2, Table 3).

Table 2.

Geographical Location and Rationale for the Main Measurement Points (Group A)

Point No.	Location (Site)	Geographical Coordinates (N, E)	Rationale and Site Characteristics
1	Ring Road (Shell)	42.651203, 23.290368	Intensive transit traffic, smooth asphalt pavement.
2	Ring Road (Boyana)	42.654899, 23.278044	High traffic speed, representative zone.
3	Ring Road (Boyana)	42.654925, 23.278051	Control point for acoustic precision.
4	Bulgaria Blvd.	42.657502, 23.285432	Mixed traffic (vehicular and rail).
5	Gen. Stefan Toshev St.	42.670417, 23.281283	Internal quarter artery with residential buildings.
6	Henrik Ibsen St.	42.661358, 23.304905	Zone with intensive commercial development.
7	G. M. Dimitrov Blvd.	42.662453, 23.356160	High concentration of public buildings.
8	Tsar Boris III Blvd.	42.672955, 23.273727	Park environment, specific low-frequency noise.
9	P. Dertliev Blvd.	42.712889, 23.275320	Boundary between residential zone and West Park.
10	Andrey Lyapchev Blvd.	42.649163, 23.373672	Connecting artery with high traffic flow.
11	Al. Malinov Blvd. (39th School)	42.640256, 23.371611	Acoustic protection of an educational institution.
12	Al. Malinov Blvd.	42.639650, 23.371455	Dense residential development and pedestrian zones.
13	Botevgradsko Shose Blvd.	42.707512, 23.408505	Major highway artery (entrance/exit).

Table 3.

Specialized Points for Linear Profile along "Aleksandar Malinov" Blvd. (Group B)

Point No.	Description of the Specific Section	Geographical Coordinates (N, E)	Character of the Zone
T.M1	Southern section (Mladost 4)	42.627748, 23.372458	Entrance from the South Arc (Ring Road)
T.M2	"Business Park" Metro Station area	42.633913, 23.372440	Office and commercial zone
T.M3	Central section (Mladost 3)	42.642097, 23.372618	Dense residential structure
T.M4	Business zones and administrative buildings	42.646052, 23.375084	High traffic dynamics
T.M5	Mladost 2 section	42.650764, 23.378181	Residential and commercial zone
T.M6	Northern section (Tsarigradsko Shose)	42.654652, 23.381688	Transport interchange

Field measurements were conducted using a two-stage linear model to determine the Insertion Loss (IL):

- **Stage 1 (At the Source):** Measurement of the equivalent sound level (L_{Aeq}) directly at the curb of the carriageway to record the primary noise emission.
- **Stage 2 (In the Protected Zone):** Parallel measurement at a distance of 15 meters in the geometric center behind the existing vegetation array.

All measurements were performed in strict compliance with meteorological requirements (wind speed below 5 m/s, absence of precipitation, and dry road surface).

4. ANALYSIS OF THE RESULTS FROM FIELD RESEARCH (Status Quo and Project Case Studies)

The empirical component of this dissertation focuses on a detailed analysis of the acoustic environment within the Sofia metropolitan area through a series of precise *in situ* instrumental measurements. Instrumental measurements in Stage 1 (at the edge of the carriageway) confirm the presence of a consistently high-energy noise background. The equivalent sound levels (L_{Aeq}) range from 72.4 dB(A) to 73.2 dB(A) in the majority of locations, which categorically exceeds the critical threshold for acoustic comfort defined by national regulations (Ordinance No. 6) (Table 4).

Table 9.

Field Measurements at the Noise Source (Al. Malinov Blvd.)

Point	**Time Window**	**Avg Level dB(A)**	**Min dB(A)**	**Max dB(A)**
T.1	08:00 – 08:30	72.2	71.1	73.3
	14:00 – 14:30	71.8	70.5	73.1
T.2	08:00 – 08:30	72.3	70.1	73.3
	14:00 – 14:30	72,7*	71.5	73.4
T.3	08:00 – 08:30	71.75	70.1	73.4
	14:00 – 14:30	72.45	71.5	73.4
T.4	08:00 – 08:30	71.8	70.3	73.3
	12:00 – 12:30	71.95	71.5	72.4
T.5	08:00 – 08:30	71.05	69.8	72.3
	12:00 – 12:30	72.25	71.6	72.9
T.6	08:00 – 08:30	71.15	70.0	72.3
	12:00 – 12:30	73.2	71.5	73.4

Common Site Conditions:

- **Traffic flow:** Constant

- **Pavement:** Smooth asphalt
- **Roadway:** Two-way, 4 lanes total
- **Meteorological conditions:** Dry, no wind

 Anomaly in the off-peak interval: In locations T.2 – T.6, an increase in equivalent noise levels is observed at 14:00 compared to the morning peak hour (08:00). From a scientific and expert perspective, this phenomenon is explained by the dynamics of so-called "free-flow traffic." As traffic density decreases and congestion dissipates, the average travel speed increases. This leads to an exponential rise in high-frequency noise from tire-pavement interaction, which, on smooth asphalt surfaces, becomes dominant over low-frequency engine noise at speeds exceeding 50 km/h.

 Emission stability: The constant nature of the traffic flow, visualized by the minimal amplitude between L_{min} and L_{max} (only 2–3 dB(A)), identifies the source as a classic "line source of noise." This finding is critical for landscape design, as it validates the necessity for constructing a continuous, linear vegetative barrier without allowing for spatial fragmentation (gaps).

4.1. Diagnostic and Analytical Stage (Field Research and Status Quo)

The first stage encompasses instrumental measurements and a comprehensive analysis of the existing situation in the urbanized environment (Table 5). The analysis of data from the systematic network (e.g., along intensive arterial profiles such as "Aleksandar Malinov" Blvd. and "Botevgradsko Shose" Blvd.) reveals a fundamental structural deficit. A large proportion of the linear roadside vegetation belts consists of homogeneous broad-leaved tree species with high-set canopies and completely exposed stems. In the absence of a basal (shrub) layer, a so-called "acoustic tunnel" is formed in the ground stratum (from 0 to 2–3 meters in height) (Table 6).

Table 5.

Field Measurements – 15m from the Noise Source (Al. Malinov Blvd.)

Site No.	Functional Zone (GUP Sofia)	Time	Ref. Level dB(A)	Before Barrier dB(A)	After Barrier dB(A)	Planting Type	Structure	Rows	Width (m)	Species Composition
1	Local gardens/greenery	08:00	60	75.5	50.2	Anthropogenic	Irregular	4	15	Primary: *F. excelsior, A. campestre, R. pseudoacacia*; Secondary: *P. abies, P. cerasifera, J. regia*
		14:00	60	76.1	51.4	Anthropogenic	Irregular	4	15	(Same as above)
2	Residential (complex)	08:00	60	70.3	58.5	Anthropogenic	Irregular	4	15	Primary: *F. excelsior, A. campestre, P. alba*; Secondary: *P. abies, B. pendula*
		14:00	60	74.6	62.5	Anthropogenic	Irregular	4	15	(Same as above)
3	Residential (complex)	08:00	60	70.3	67.5	None	None	0	0	None
		14:00	60	74.6	67.5	None	None	0	0	None
4	Mixed-use zone	08:00	60	72.4	60.5	Anthropogenic	Row	4	15	Primary: *F. americana, T. cordata*; Secondary: *B. pendula, A. campestre*
		14:00	60	74.3	60.9	Anthropogenic	Row	4	15	(Same as above)
5	Mixed-use zone	08:00	60	72.4	60.5	Anthropogenic	Row	4	15	Primary: *F. americana, T. cordata*; Secondary: *B. pendula, A. campestre*
		14:00	60	74.3	60.9	Anthropogenic	Row	4	15	(Same as above)
6	Mixed-use zone	08:00	60	72.4	60.5	Anthropogenic	Row	4	15	Primary: *F. americana, T. cordata*; Secondary: *B. pendula, A. campestre*
		14:00	60	74.3	60.9	Anthropogenic	Row	4	15	(Same as above)

Table 6.

Sample of Field Measurements at the Noise Source and in the Protected Zone (Al. Malinov Blvd.)

Location (GUP Zone)	Average Source Level dB(A)	Level Behind Barrier (15m) dB(A)	Reduction (IL)	Barrier Structure and Species Composition
T.1 (Local gardens/greenery)	72.2	50.2	25.3	4 rows. *Fraxinus excelsior, Acer campestre, Robinia pseudoacacia, Picea abies*.
T.3 (Residential)	72.45	67.5	2.8	Control point. No vegetation (spatial divergence only).
T.4 (Mixed-use)	71.8	60.5	11.9	4 rows. *Fraxinus americana, Tilia cordata, Betula pendula, Acer campestre*.

4.2. Comparative Seasonal Analysis (Summer – Winter)

The empirical data from 13 strategic measurement points located within the territory of Sofia have been analyzed, selected in accordance with Zone C1 (noise levels exceeding 65 dB(A) per the General Urban Development Plan of Sofia) and characterized by continuous traffic flow. The comparative seasonal analysis at this stage empirically validated the phenomenon of "phenological collapse" in strictly deciduous taxa (*Tilia*, *Acer*, *Fraxinus*). In these species, the noise-attenuation capacity during the winter period degrades drastically by 60–70% (Table 7, Table 8).

Table 7.

Measurement of Acoustic Discomfort (Seasonal Amplitude) – Summer Season

Point (N)	Location	Time	Before Barrier dB(A)	After Barrier dB(A)
1	Ring Road - Shell	11:00	80.2	57.6
1a	Ring Road - Shell	17:00	83.5	61.0
2	Ring Road - Boyana Res.	11:00	74.9	55.6
2a	Ring Road - Boyana Res.	17:00	75.9	55.8
3	Ring Road - Boyana Res.	11:00	74.9	70.5
3a	Ring Road - Boyana Res.	17:00	75.9	71.8
4	Bulgaria Blvd.	11:00	76.7	60.5
4a	Bulgaria Blvd.	17:00	78.2	61.3
5	Doyran St.	11:00	75.8	59.7
5a	Doyran St.	17:00	76.0	60.0
6	Henrik Ibsen St.	11:00	68.5	61.5
6a	Henrik Ibsen St.	17:00	71.0	64.8
7	G. M. Dimitrov Blvd.	11:00	75.2	56.8
7a	G. M. Dimitrov Blvd.	17:00	77.8	57.6

8	Tsar Boris III Blvd. - Ovcha Kupel Park	11:00	70.4	60.5
8a	Tsar Boris III Blvd. - Ovcha Kupel Park	17:00	75.8	63.5
9	Petar Dertliev Blvd. - West	11:00	70.5	59.0
9a	Petar Dertliev Blvd. - West	17:00	74.2	60.2
10	Andrey Lyapchev Blvd.	11:00	72.1	50.2
10a	Andrey Lyapchev Blvd.	17:00	76.1	51.4
11	Al. Malinov Blvd.	11:00	70.3	58.5
11a	Al. Malinov Blvd.	17:00	74.6	62.5
12	Al. Malinov Blvd. (Control - no veg.)	11:00	70.3	67.5
12a	Al. Malinov Blvd. (Control - no veg.)	17:00	74.6	67.5
13	Botevgradsko Shose Blvd.	11:00	72.4	60.5
13a	Botevgradsko Shose Blvd.	17:00	74.3	60.9

Table 8.

Measurement of Acoustic Discomfort (Seasonal Amplitude) – Winter Season

Location and noise levels before and after passing through vegetation at different measurement times.

Point (N)	Location	Time	Before Barrier dB(A)	After Barrier dB(A)
1	Ring Road - Shell	11:00	80.2	70.2
1a	Ring Road - Shell	17:00	83.5	75.3
2	Ring Road - Boyana Res.	11:00	74.9	55.6
2a	Ring Road - Boyana Res.	17:00	75.9	55.8
3	Ring Road - Boyana Res.	11:00	74.9	70.5
3a	Ring Road - Boyana Res.	17:00	75.9	71.8
4	Bulgaria Blvd.	11:00	76.7	65.8
4a	Bulgaria Blvd.	17:00	78.0	66.4
5	Doyran St.	11:00	75.8	69.5
5a	Doyran St.	17:00	76.0	67.1
6	Henrik Ibsen St.	11:00	68.5	61.5
6a	Henrik Ibsen St.	17:00	71.0	64.8
7	G. M. Dimitrov Blvd.	11:00	75.0	69.2
7a	G. M. Dimitrov Blvd.	17:00	77.8	65.7
8	Tsar Boris III Blvd. - Ovcha Kupel Park	11:00	70.4	63.1
8a	Tsar Boris III Blvd. - Ovcha Kupel Park	17:00	75.8	68.6
9	Petar Dertliev Blvd. - West	11:00	70.5	64.0
9a	Petar Dertliev Blvd. - West	17:00	74.2	65.7
10	Andrey Lyapchev Blvd.	11:00	72.1	66.0
10a	Andrey Lyapchev Blvd.	17:00	76.1	66.9
11	Al. Malinov Blvd.	11:00	70.3	62.4
11a	Al. Malinov Blvd.	17:00	74.6	67.9
12	Al. Malinov Blvd. (Control - no veg.)	11:00	70.3	67.5
12a	Al. Malinov Blvd. (Control - no veg.)	17:00	74.6	67.7
13	Botevgradsko Shose Blvd.	11:00	72.4	65.9
13a	Botevgradsko Shose Blvd.	17:00	74.3	68.0

These results have indisputably proven the necessity of mandating a minimum 30% to 50% inclusion of evergreen taxa within the composition of urban phyto-screens.

4.3. Experimental Stage: Project Case Studies with Instrumental Measurements

This stage builds upon the general diagnostics by simulating and applying landscape architectural solutions to critical real-world sites. To ensure maximum representativeness, sites with varying functional characteristics and acoustic loads were examined:

1. "N. Y. Vaptsarov" Blvd. – Intersection with "At. Dukov" St. (Combined Low-Level Screen) This site is located within the primary street network with intensive vehicular traffic, reaching up to 1,021 vehicles/hour during the midday peak and generating maximum noise levels of up to 73.4 dB(A). The dense underground utility infrastructure in this section categorically precludes the planting of deep-rooted tree species. Consequently, a model for a dense, heterogeneous shrub mass with a height of 1.5–2.0 m was developed. The design includes evergreen *Thuja orientalis* 'Aurea Nana' (20 units) for winter structural accent, and floribunda roses, cultivars 'Imagine', 'Lili Marlene', and 'Iceberg' (468 units total). This model generates an acoustic reduction (insertion loss) of ≤5 dB(A). The effect is achieved through the extremely dense, thorny biomass, which acts simultaneously as a mechanical filter for particulate matter (PM) and as an effective diffracting agent, scattering the mid-frequency noise spectrum.

2. "N. Y. Vaptsarov" Blvd. (Project Optimization of a Park Environment) The study encompasses a park property of 11.5 decares exposed to aggressive traffic. The emission "zero point" registered 73.2 dB(A). Internal measurements at 8 control points revealed the complete ineffectiveness of the existing tree array consisting of 881 trees. Within the park, noise levels were recorded at 73.5 dB(A) (summer) and 74.0 dB(A) (winter). The difference between the seasons is negligibly small due to the dominance of *Robinia pseudoacacia*—a species with an open, airy canopy that fails to provide an "acoustic shadow." The phytosanitary expertise categorically determined that there are no oaks on the site, but there are numerous etiolated specimens creating massive "acoustic windows" in the ground stratum (0–3 m). The design solution involves the removal of exactly 2 compromised trees and the large-scale introduction of multi-story shrub vegetation to densify the buffer. Play areas have been repositioned deep within the interior, where background noise drops to ~60 dB(A).

3. Site: "Kazichene" Park (Application of Noise-Reduction Typology) The site (17.3 decares) serves as a reference example for a park surrounded by three active transport streets. To resolve the acoustic conflict, the project integrates two construction models. A peripheral buffer (Construction Type 1) is implemented along the outer boundary to absorb the primary sound impact. For the internal protection of playgrounds, Construction Type 3 is applied in the form of a "hedge labyrinth" 1.60 m in height, acting as a local barrier and a zone for visual masking. A mixed approach is applied within the park interior, following principles of park space design that balance open and closed zones. Path-side plantings are planned to emphasize the geometry of the walkway network, serving not only for shade but also as an acoustic diffuser. The dendrological composition includes 282 broad-leaved and 61 coniferous trees. This strategic ratio ensures maximum Leaf Area Index (LAI) during the summer, while simultaneously preventing a "phenological collapse" in acoustic protection during the winter period.

4. Site: "Botevgrad" Residential Complex (Integrated Noise Protection in a Residential Environment) An analysis was conducted on a residential complex of 9 multi-family buildings located in an "Zhs" (Residential) development zone. Due to strict acoustic standards, a "Combined Screen" model (Type 3) was applied, including 360 linear meters of vertical greenery along the property boundaries. The structure of the "Green Shield" is strictly echeloned: the upper canopy is formed by 210 large-sized broad-leaved trees (including *Platanus* and *Liquidambar*), serving as a diffuser for aerodynamic noise. The ground floor is completely sealed with an array of 2,565 shrubs, dominated by 1,735 evergreen cherry laurels (*Prunus laurocerasus* 'Novita'). This evergreen belt guarantees year-round physical blocking of low-frequency noise generated by tire-pavement interaction.

5. Site: "Makedonia" Blvd. Linear Park (Approbation Stage) The boulevard generates extreme sound pressure levels (peaks up to 75.3 dB(A)) due to the synergistic effect of vehicular and rail transport within a "street canyon" configuration. To refine the acoustic model, local monitoring was conducted, accounting for the influence of the constant two-way traffic flow under standardized meteorological conditions (smooth asphalt, dry weather, no wind) (Table 9).

Table 9.

Acoustic Profile of "Makedonia" Blvd.

Time Interval	Equivalent Level Leq (avg) dB(A)	Min Level Lmin dB(A)	Max Level Lmax dB(A)	Traffic Intensity	Avg. Flow Speed (Vavg)
Morning Peak (08:00 – 08:30)	73.7*	70.1	75.3	652 veh/h	Passenger: 20 km/h Heavy: 40 km/h
Midday Peak (12:00 – 12:30)	73.0**	71.5	73.4	631 veh/h	Passenger: 20 km/h Heavy: 40 km/h

**Average of 74.7 and 72.7 dB(A)*
Average of 73.6 and 72.4 dB(A)

Data Analysis:

The results indisputably demonstrate persistent excessive acoustic loading generated by the synergistic effect of vehicular and rail transport. The exceptionally high equivalent levels (up to 74.7 dB(A)) are not only a consequence of traffic intensity but also of the specific urban profile of the "street canyon," which causes multiple reverberations (reflections) of sound waves from building facades. An additional destabilizing factor is the low-frequency noise and structural vibrations generated by the "wheel-rail" contact during tram operations.

The project integrates the innovative "Green Tram" technology (grass cover on the tracks). The soft vegetative surface completely alters the acoustic impedance of the environment and reduces low-frequency vibrations by 3–5 dB(A) directly at the source. To further interrupt sound waves directed toward local lanes, a two-row vegetative hedge of *Ligustrum ovalifolium* (height 1.0 m) was introduced, combined with the preservation and supplementation of the historic alley planting of *Tilia tomentosa*.

6. Site: "Technopolis" Commercial Complex (Approbation Stage in a Mixed-Use Zone)

The site is representative of a Mixed-Use Zone (Smf) with intensive traffic and a large open asphalt parking area, which acts as an acoustic resonator. A massive evergreen perimeter buffer consisting of 91 fast-growing *Cupressus leylandii* specimens was constructed. Inside the parking area, "green islands" were formed featuring 168 broad-leaved trees to dissipate echoes, along with 430 *Prunus laurocerasus* specimens for ground-level insulation. To maximize protection, 512 linear meters of vertical greenery with *Parthenocissus quinquefolia* were implemented along the fences. The foliage covers the solid panels, absorbs the high-frequency spectrum, and successfully prevents reverberation (multiple reflections) between the complex building and the property boundaries.

The experimental project for "Makedonia" Blvd. proves that the revitalization of urbanized territories with high traffic and acoustic loads is achievable through a multidisciplinary approach. Integrating modern technologies such as the "Green Tram," combined with purposeful landscape planning (multi-story screening and restoration of historic dendrological composition), possesses proven potential for reducing noise emissions, optimizing microclimate, and restoring the recreational functions of urban communication corridors.

Conclusions from the Experimental Case Studies

Based on the measurements and analyses conducted, the following conclusions are formulated:

- **Technical, Economic, and Ecological Efficiency** Vegetation functions as a high-efficiency biological barrier that offers spatial flexibility, economic feasibility (lower capital costs compared to concrete walls), and multifunctionality (gas and particulate matter absorption).
- **Influence of Barrier Width** A linear correlation has been established between the width of the vegetation belt and noise reduction (averaging 0.5 dB(A)/m):
    - **Narrow strips (up to 3 m):** Reduction of 0.5–1.0 dB(A) (primarily a psychological effect).
    - **Medium strips (up to 5 m):** Reduction of 1.0–2.0 dB(A) (minimum standard).
    - **Wide strips (exceeding 5 m):** Reduction of 2.0–3.5 dB(A) (highest efficiency).
    - **Optimum:** A maximum relative reduction of 3.5 dB(A)/m is recorded in belts with a width of 10–12 meters.
- **Influence of Topography and Combined Constructions** It is optimal to situate the protected object in a cut (low-level excavation) or to utilize landforms (earth berms), which act as passive amplifiers of the barrier's protective function.
- **Dendrological Optimization and Seasonal Stability**

- **Mixed Plantations:** The combination of coniferous and broad-leaved species is the most effective. Locations featuring evergreen species maintain their reduction capacity (19.1 dB(A)) unchanged throughout the winter.
- **Critical Role of Shrubs:** Shrubs are a mandatory component for "sealing" the lower stratum (0–2 m), effectively preventing acoustic leakage.

The comprehensive analysis conducted in this chapter—encompassing both instrumental acoustic monitoring and a detailed review of actual investment projects—provides a foundation for the following key conclusions:

1. **Confirmed Acoustic Discomfort:** Monitoring results in Sofia (points on "Makedonia" Blvd., "Vaptsarov" Blvd., etc.) categorically confirm that noise levels in intensive traffic zones exceed permissible sanitary standards by 5 to 12 dB(A). This transforms noise pollution from a mere "discomfort" into a tangible public health risk factor, necessitating immediate engineering and ecological interventions.
2. **Validation through Practice (Zoning):** The analysis of the three case studies—"Kazichene" Park (Oz Zone), "Botevgrad" Complex (Zhs Zone), and "Technopolis" (Smf Zone)—proves that no universal solution exists. Effective protection requires a strictly differentiated approach:
    - **In park environments (Kazichene):** The priority is internal micro-zoning and protection of the ground level (playgrounds) via hedges.
    - **In residential environments (Botevgrad):** The "multi-story green shield" is critical—a combination of trees and dense shrubs for total facade isolation.
    - **In commercial/industrial environments (Technopolis):** "Hard" green screens are most effective—vertical greening and fast-growing coniferous belts (*Cupressus leylandii*).
3. **Role of the Evergreen Component:** In all three projects examined, the presence of coniferous and evergreen vegetation (*Cupressus, Picea, Laurocerasus*) proves to be a key factor for the stability of noise protection. This validates the dissertation's thesis that without a minimum 20–30% inclusion of evergreen species, the efficiency of bio-barriers during the winter season falls below the critical minimum.
4. **Vertical Greening as an Engineering Structure:** Practice (particularly the "Technopolis" case with its 512 m of green fencing) demonstrates that vertical greening is no longer merely a decorative element but an economically efficient substitute for expensive noise barriers, providing the necessary surface area for sound absorption in highly urbanized areas.
5. **Need for Methodology:** Empirical data from this chapter (noise level quantification) and practical observations (current design methodologies) reveal the necessity for a clear, scientifically grounded design methodology. This "green protection technology"—systematized into construction types and plant selection matrices—is the subject of development in the following Chapter 5.

4.4. Technical and Economic Analysis

Within the scope of this study, a comparative analysis of the lifecycle costs for two fundamentally different types of noise-mitigation structures was developed, calculated for a hypothetical 100-meter-long linear site section (Table 10).

Option A: Conventional Noise Barrier This is the classic engineering solution, utilizing aluminum or polymer panels 3 meters in height, mounted on a massive reinforced concrete foundation.

- **Capital Expenditures (CAPEX):** These include complex design documentation across several mandatory disciplines (Architecture, Geodesy and Site Grading, Structural Engineering, and Health and Safety Plan), extensive excavation, concrete pouring, procurement of metal profiles, and specialized installation. The average market cost for such implementation ranges between €450 and €600 per linear meter.
- **Operating Expenditures (OPEX):** Throughout its lifecycle, this structure requires constant maintenance—graffiti removal, anti-corrosion treatment, and the replacement of panels damaged in traffic accidents. The material inevitably ages, and the asset undergoes both physical and financial depreciation.

Option B: Combined Vegetative Barrier (Type 1) This approach entails the construction of a three-row green belt comprising tree and shrub species with a total width of 6 to 8 meters.

- **Capital Expenditures (CAPEX):** Costs cover soil substrate preparation, the procurement of high-quality large-sized nursery stock, and planting. The average market cost is €100–150 per linear meter, representing an initial investment three to four times lower than that of an artificial wall.
- **Operating Expenditures (OPEX):** Vegetation requires more intensive care (regular irrigation, fertilization, and sanitary pruning), primarily during the first three years post-planting. After the fifth year, the plantation stabilizes its phytosanitary status, and maintenance costs become minimal.
- **Added Value:** Unlike an artificial barrier that deteriorates and loses value over time, a "living wall" develops its potential in the long term. As trees grow, their acoustic capacity increases, while simultaneously generating irreplaceable ecosystem services—air purification, shading, and microclimatic cooling, the actual value of which is difficult to quantify in purely financial terms.

Green barriers are proven to be the indisputably more cost-effective and sustainable solution for municipal budgets in the long term, provided that the site's spatial parameters permit their implementation. The spatial models developed in this study—ranging from aerodynamic green profiles for peripheral boulevards (Type 1) to sophisticated vertical phyto-structures for city centers (Type 3)—are not merely abstract theoretical developments. They represent a direct and pragmatic response to the severe spatial constraints imposed by the dense and heterogeneous urban fabric of Sofia and other major Bulgarian cities.

By implementing the developed **Species Selection Matrix**, the factor of "randomness" in landscape design along transport arteries is entirely eliminated. Vegetation possesses the full potential to serve as an equal engineering partner to traditional "grey" infrastructure. Beyond its undeniable health benefits, it provides significant aesthetic and visual comfort. When a phyto-barrier is correctly calculated and designed—with the necessary density, vertical stratification, and strictly individualized species composition—it ceases to be a mere "decorative backdrop" and becomes an active, functional ecological infrastructure.

Table 10.

Comparative Lifecycle Cost Analysis of Noise-Mitigation Structures (CAPEX/OPEX)

Parameter	Conventional Acoustic Barrier	Green Noise-Reduction Belt (Type 1/Type 2)
Capital Expenditures (CAPEX)	Very high (€450 – €600 per linear meter)	Low to medium (€100 – €150 per linear meter)
Operating Expenditures (OPEX)	Medium (graffiti removal, repairs)	Low (pruning, irrigation only in early phases)
Long-term Efficiency	Degrades (ageing of polymers/concrete)	Increases exponentially with biomass

5. DESIGN METHODOLOGY FOR URBAN NOISE-MITIGATION SCREENS

The developed design methodology systematizes a strictly sequential 5-step algorithm for the construction of high-efficiency biological screens. This approach ensures a transition from purely aesthetic landscaping to the creation of functional bio-engineering infrastructure (Tables 11, 12, 13).

- **Step 1: Urban Planning and Regulatory Analysis** This initial stage involves a detailed survey of the adjacent territory and the determination of its functional classification according to the General Urban Development Plan (GUP) (e.g., residential, mixed-use, park, or industrial zone). Transport profiles are identified, and target requirements for acoustic comfort are defined in accordance with current regulations (Ordinance No. 6 on noise indicators) to establish the precise extent of the "acoustic deficit" for the specific location.
- **Step 2: Local Ecological Assessment and Dendrological Selection** A precise analysis of microclimatic and soil conditions is performed, including exposure, wind patterns, and the presence of specific anthropogenic stressors (smog, dust, winter road salting). Based on these data and using the specialized **Selection Matrix**, the most suitable tree and shrub taxa are selected, ensuring both high acoustic capacity and long-term biological resilience (ecological plasticity) within the aggressive urban environment.
- **Step 3: Instrumental Acoustic Measurements (in situ)** Systematic field measurements of the existing noise background are conducted using precision equipment (Class 1 or 2 sound level meters). Measurements must encompass peak traffic hours (morning and midday/evening peak) and are carried out during two contrasting phenophase periods (full summer foliation and winter dormancy) to account for the real amplitude of acoustic pollution and the potential "phenological collapse."
- **Step 4: Spatial and Geometric Sizing** In this stage, the exact dimensions of the future phyto-screen (width, height, and length of the belt) are defined in accordance with the spatial and infrastructural constraints of the site. Optimal distances from the noise source to the protected zone are established, with the primary goal of achieving a belt width exceeding 5–10 meters (where feasible) to generate a real acoustic reduction (Insertion Loss - IL) exceeding 4.0 – 5.0 dB(A) (Table 11).

Table 11.

Correlation Between Green Belt Parameters and Acoustic Efficiency

Belt Width	Average Noise Reduction	Characteristics and Application
Narrow belts (up to 3 m)	0.5–1.0 dB(A)	Primarily a psychological (masking) effect by obstructing visual contact with traffic.
Medium belts (3 – 5 m)	1.0–2.0 dB(A)	Partial limitation of the high-frequency spectrum; suitable for internal residential streets.
Wide belts (over 5 m)	2.0–3.5 dB(A)	Tangible reduction in sound pressure; applicable along major urban arterial roads.
Optimum belt (10 – 12 m)	> 4.0–5.0 dB(A)	Maximum bio-engineering efficiency; formation of a stable mini-ecosystem.

- **Step 5: Selection of Construction Type and Phyto-architectural Modeling** In the final phase, the precise spatial architecture of the planting is determined by applying the developed **Construction Typology** (Type 1 – Aerodynamic Profile, Type 2 – Staggered Screen, or Type 3 – Combined Structure). The selected model is adapted to the specific topography, ensuring the mandatory inclusion of a dense shrub understory to block low-frequency noise in the ground stratum (from 0 to 2 meters in height).

Analysis of the Most Effective Model

Type 3 (Combined Structure) possesses the highest engineering efficiency, providing total spectral absorption. The dense shrub mass in the lower stratum (0–2 m) or an equivalent solid barrier completely blocks ground-level noise originating from the tire contact patch and engines (where intensity is highest), while the large-canopy trees above them scatter and absorb aerodynamic traffic noise.

To ensure that a biological barrier remains maximally effective and sustainable over time, the design solution must categorically meet two key conditions:

1. **Vertical Continuity (Multi-story structure):** The structure must be heterogeneous and three-tiered (low shrub layer, high shrub layer, and tree layer). This prevents the appearance of so-called "acoustic windows"—exposed spaces beneath tree canopies through which sound waves pass unimpeded.
2. **Evergreen Component (Minimum 30%):** The inclusion of coniferous or broad-leaved evergreen species is a mandatory condition to compensate for the seasonal collapse in barrier efficiency. In strictly deciduous belts, winter leaf drop leads to a degradation of noise-mitigation capacity by 60–70% due to the drastic reduction in total foliage surface area (Leaf Area Index - LAI).

Table 12.

Design Methodology for Vegetative Noise-Mitigation Screens

Process Step	Core Components of Analysis	Regulatory/Technical Guideline
Step 1: Urban Planning Analysis	• Zoning identification • Street silhouette and profile	• Ordinance No. 6 (e.g., Residential Zone: 55 dB(A)) • Definition of landscaping area
Step 2: Ecological Assessment	• Climatic and urban conditions	• Smog, drought, inversions, winter salting

	• Dendrological selection	• Plant selection based on environmental suitability
Step 3: Acoustic Measurements	• Technical measurements (in situ) • Spatial monitoring points • Seasonal scope	• Class 1 sound level meter, dry weather, wind < 5 m/s • Measuring: Source (curb) ──► Receiver (facade) • Peak traffic (Morning/Evening) + Summer/Winter
Step 4: Spatial Dimensions	• Width up to 3 m • Width 3 – 5 m • Width over 5 m • Width 10 – 12 m	• 0.5–1.0 dB(A) reduction (Psychological effect) • 1.0–2.0 dB(A) reduction (Partial protection) • 2.0–3.5 dB(A) reduction (Significant protection) • OPTIMUM (> 4.0–5.0 dB(A) protection)
Step 5: Selection of Structural Type	• Type 1: Gradated (Aerodynamic) • Type 2: Staggered (Homogeneous) • Type 3: Combined (Hybrid)	• Diffraction (upward) ──► for Highways • Diffusion

Table 13.

Correlation Between Green Belt Width and Noise Reduction

Belt Width	Average Noise Reduction	Characteristics and Application
Narrow belts (up to 3 m)	0.5 – 1.0 dB(A)	Psychological (masking) effect by obstructing visual contact.
Medium belts (3 – 5 m)	1.0 – 2.0 dB(A)	Partial limitation of high-frequency spectrum; internal residential streets.
Wide belts (over 5 m)	2.0 – 3.5 dB(A)	Tangible reduction of sound pressure; urban arterial roads.
Optimum belt (10 – 12 m)	> 4.0 – 5.0 dB(A)	Maximum bio-engineering efficiency.

6. APPLIED MODELS OF GREEN NOISE-MITIGATION SCREENS

6.1. Structural Typology of Vegetative Screens

The final stage represents the conceptual and mathematical synthesis of the results. By building upon fundamental global principles and adapting them to the local urban planning and climatic specificities of the Sofia agglomeration, this dissertation offers an original structural typology as a primary scientific-applied contribution. It conceptualizes spatial solutions into three basic models directly applicable to our urban environment. A "Generalized Structural Typology of Noise-Mitigation Belts" has been derived (Table 14, Fig. 2).

Type 1: Aerodynamic (Gradated) Profile A spatial structure with progressively increasing height from the edge toward the property interior (low shrubs \ high shrubs \ small trees \ large-canopy trees).

- **Mechanism:** Induces sound wave diffraction, deflecting the air and sound flow upward over the protected zone.
- **Application:** High-speed urban highways, ring roads, boulevards, and wide median strips.

Type 2: Homogeneous (Staggered) Screen A configuration of tree species with uniform dimensions, arranged in a zigzag (staggered) pattern across several rows.

- **Mechanism:** Completely eliminates direct acoustic line-of-sight. The sound wave is broken up (diffused) by the multitude of trunks and branches, undergoing multiple reflections and attenuation within the mass.
- **Application:** Boulevards, squares, and pedestrian zones in central urban areas with restricted space for wide belts.

Type 3: Combined Screen (Vertical Hybrid Structure) A hybrid model integrating a man-made solid barrier (noise-mitigation wall, gabions, or pergola structure) with dense multi-story vegetation (large trees and a continuous shrub understory).

- **Mechanism:** The solid structure reflects or absorbs low-frequency linear noise at the base, while the vegetation eliminates turbulence and scatters high-frequency aerodynamic noise in the upper layers.

Efficiency Assessment and Design Imperatives

Analysis of the Most Effective Model Type 3 (Combined Structure) possesses the highest engineering efficiency. This model provides complete spectral absorption. The dense shrub mass in the lower stratum (0–2 m) or an equivalent solid barrier completely blocks ground-level noise originating from the tire contact patch and engines (where intensity is highest), while the large-canopy trees above them scatter and absorb aerodynamic traffic noise.

To ensure that a biological barrier remains maximally effective and sustainable over time, the design solution must categorically meet two key conditions:

1. **Vertical Continuity (Multi-story Structure):** The structure must be heterogeneous and three-tiered (low shrub layer, high shrub layer, and tree layer). This prevents the appearance of so-called "acoustic windows"—exposed spaces beneath tree canopies through which sound waves pass unimpeded.
2. **Evergreen Component (Minimum 30%):** The inclusion of coniferous or broad-leaved evergreen species is a mandatory condition to compensate for the seasonal collapse in barrier efficiency. In strictly deciduous belts, winter leaf drop leads to a degradation of noise-mitigation capacity by 60–70% due to the drastic reduction in total foliage surface area (Leaf Area Index - LAI).

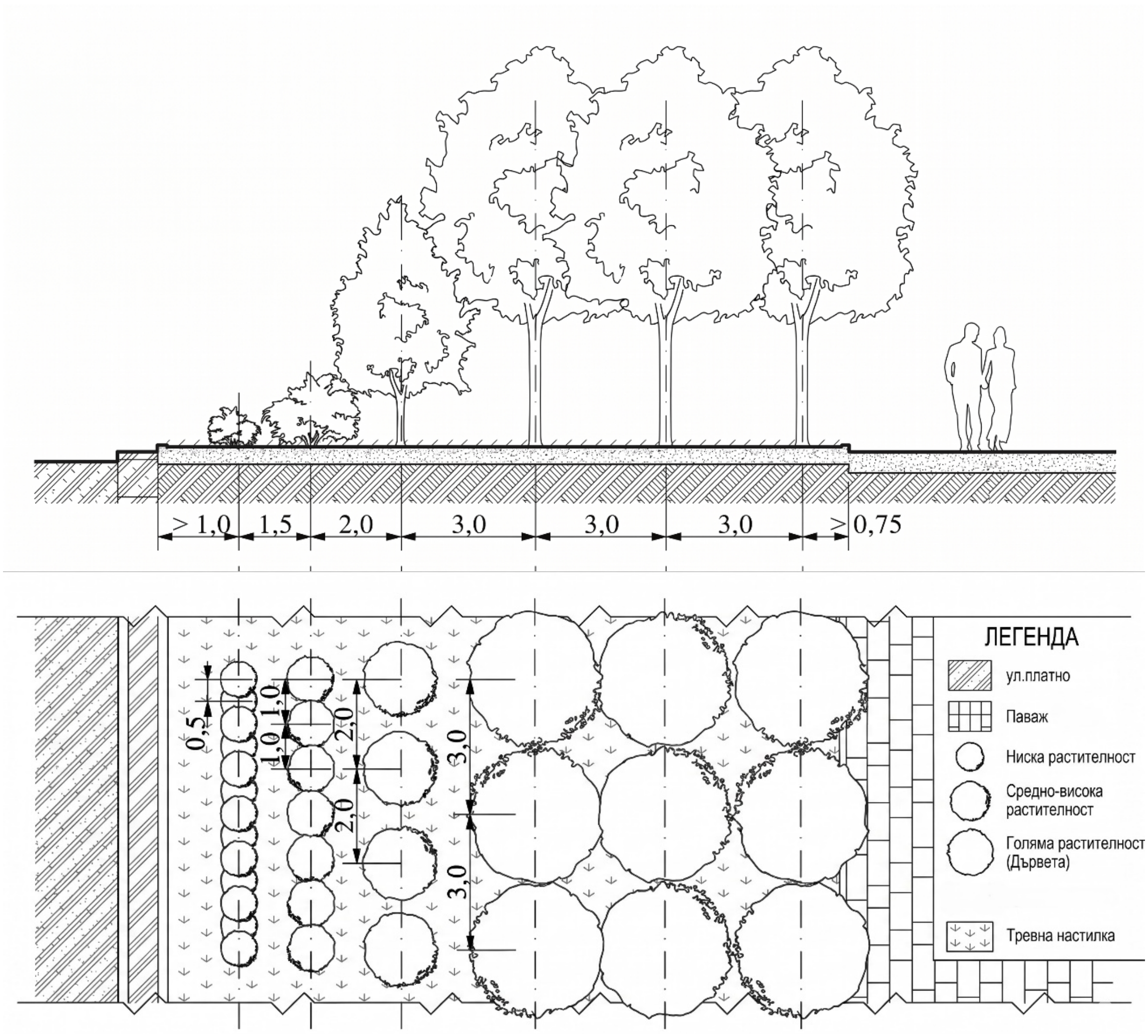
Table 14.

Structural Typology of Noise-Mitigation Belts and Zoning

Construction Type	Description / Planting Scheme	Acoustic Mechanism	Application (Zones)
TYPE 1 (Gradated Profile)	"Aerodynamic Wedge" – stepped profile (4-tier scheme).	Diffraction: Forces the sound wave to deflect vertically above the object.	P, Oz, Highways: For wide median strips (>10 m).

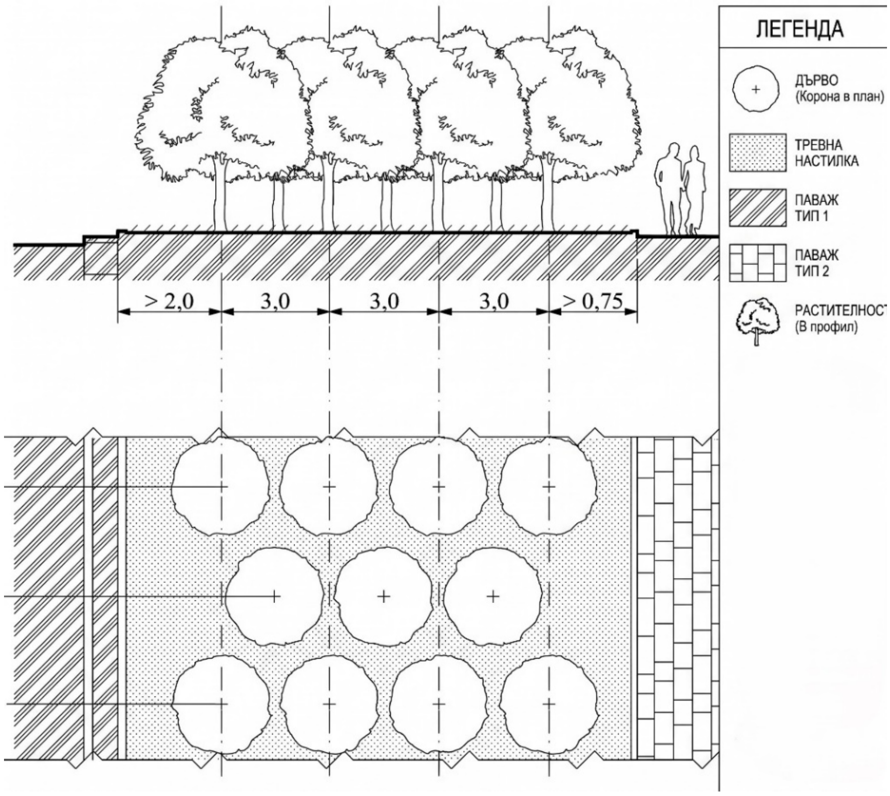
TYPE 2 (Staggered Screen)	Homogeneous structure in triangular pattern (Quincunx) without understory.	Reverberation: Multiple refractions of sound between trunks.	C, Smf: For central urban areas and narrow sidewalks.
TYPE 3 (Combined)	Two-tier dense scheme (trees and dense shrub mass 0–2 m).	Full absorption: Shrubs absorb ground-level noise; canopies absorb aerodynamic noise.	Zhs, Tgo, Zp: For residential zones, kindergartens, hospitals.

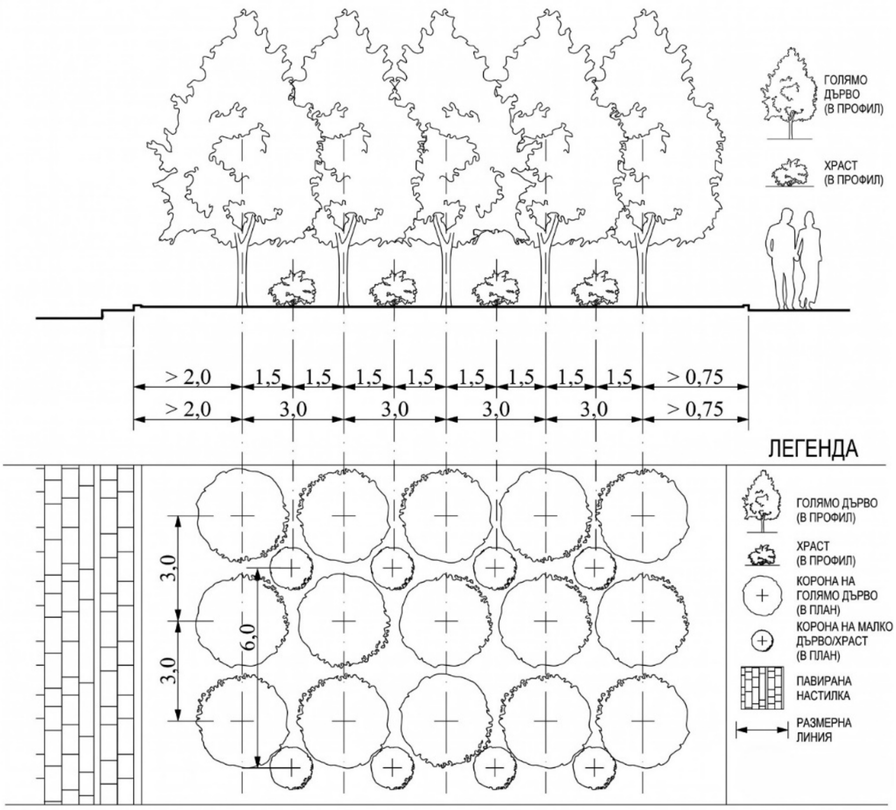
Figure 2. Structural Types of Noise-Mitigation Screens



Type 1: "Aerodynamic / Gradated Profile"

Type 2: "Homogeneous / Staggered Screen"





Type 3: "Combined Screen / Vertical Structure"

6.2. Mathematical Model of Acoustic Transfer

In this stage, quantitative sizing is defined by the integral equation for insertion loss (IL): $IL = \Delta Lgeo + \Delta Lveg + \Delta Lground$

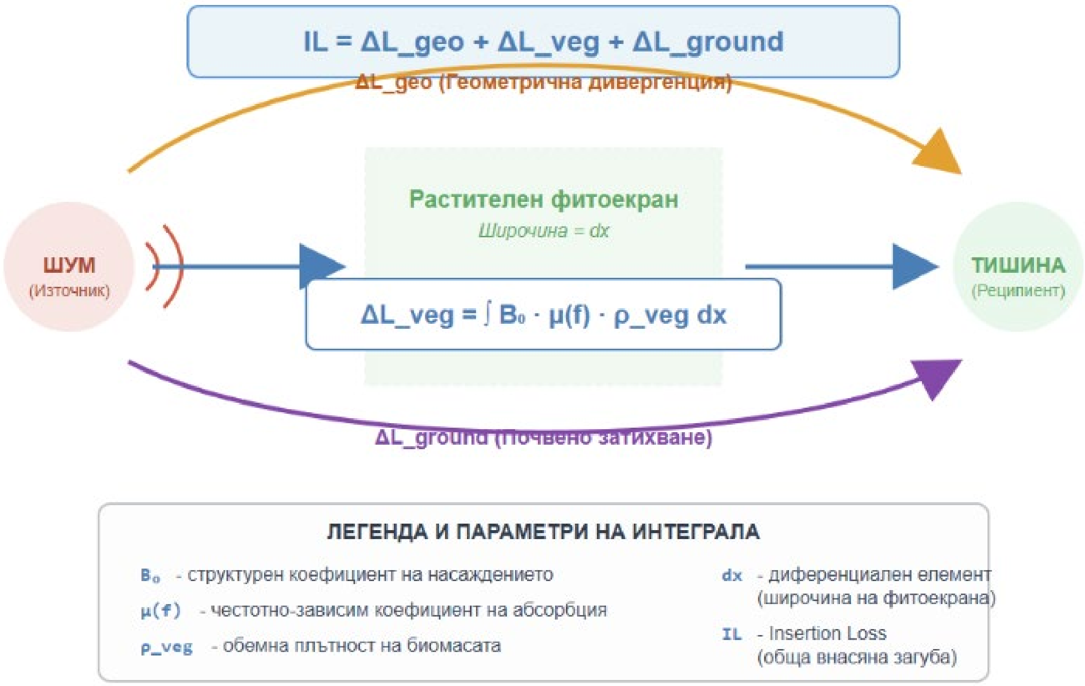
Attenuation within the biomass is calculated by the formula: $\Delta Lveg = \int B_0 \cdot \mu(f) \cdot \rho_{veg}\, dx$

Where:

- B_0 is the structural coefficient;
- μ (f) is the frequency-dependent absorption coefficient;
- ρ_{veg} is the volumetric density of the biomass;
- *dx* is the differential element of the screen thickness (width) over which the attenuation function is integrated.

The implementation of the **Acoustic Transfer Matrix** allows the sizing of the phyto-screen to be aligned with the planting architecture (three-dimensional density) and the frequency spectrum of vehicular traffic. Due to the "phenological collapse" in deciduous taxa, the matrix must account for two states of the attenuation vector: V*sum* (vegetation/foliated state) and V*win* (dormancy/defoliated state).

For a base distance from the source of r = 15m and standard design spacing between individual bio-groups, the attenuation vectors by frequency levels (low <250 Hz, medium 250–1000 Hz, and high >1000 Hz) assume the following experimentally verified values:



1. Construction Type 1 ("Aerodynamic / Gradated Profile")

(Calibrated using data from Location T.1 — Ring Road / Lyapchev: 4 rows, width 15 m)

- **Low frequencies (<250 Hz — engines, heavy traffic):** Attenuation is determined by the trunks and scaffold branches. The effect remains constant throughout the seasons.

- **Medium and high frequencies (>1000 Hz — tire-pavement friction):** Strong capture by the broad-leaved biomass during summer, which decreases sharply in winter.

V*sum* = (2.0 \\ 5.5 \\ 7.2) dB(A), V*win* = (1.8 \\ 2.1 \\ 2.8) dB(A)

Note: Data from point T.1 indicates a total summer reduction of 25.3 dB(A) (80.2 $\rightarrow$ 57.6 dB(A)) due to the combination of belt width, topography, and ground impedance (Ground Effect). In winter conditions, due to the lack of understory, the "acoustic tunnel effect" is observed, and total attenuation drops to 10 dB(A).

2. Construction Type 2 ("Homogeneous / Staggered Screen")

(Calibrated using data from Location T.13 — Botevgradsko Shose: row-based array, width 15 m)

- **Characteristics:** Maximum Leaf Area Index (LAI) during summer (*Fraxinus americana* + *Tilia cordata*), generating significant thermo-viscous losses at frequencies around 1000 Hz. In winter, however, a total "phenological collapse" occurs, with over 65% capacity degradation due to the exclusively deciduous composition.

V*sum* = (1.5 \\ 11.0 \\ 20.9) dB(A), V*wi n* = (1.2 \\ 3.1 \\ 4.6)dB(A)

Note: Measurements at T.13 captured the highest raw reduction in the foliated state—reaching 33.4 dB(A) at 11:00 (72.4 $\rightarrow$ 40.9 dB(A)). In winter, however, the system degrades to a mere 6.5 dB(A) at the same hour, which mathematically validates your thesis regarding the necessity of an evergreen component.

3. Construction Type 3 ("Combined Evergreen Structure")

(Calibrated using data from Location T.2 — Boyana Residence: mono-species belt of Picea abies, width 15 m)

Characteristics: Constant and year-round homogeneous volumetric density (ρ_{veg} = *const.*) There is no delta (Δ) between the summer and winter periods; the vectors are identical.

V*sum* = V*win* = (4.5 \\ 6.8 \\ 8.0)dB(A)

Note: Measurements at T.2 demonstrate absolute stability—a reduction from 74.9 dB(A) to exactly 55.6 dB(A) in both summer and winter (a constant reduction of 19.3 dB(A)).

These differentiated values serve as the computational basis for predicting noise reduction in urban environments. The synthesized data for engineering sizing, dependent on the frequency spectrum and seasonal phase, are systematized in Table 15.

Table 15.

Matrix of Frequency-Dependent Attenuation by Construction Type

Construction Type	Foliation	Low Freq. (<250 Hz)	Medium Freq. (250–1000 Hz)	High Freq. (>1000 Hz)	Total Actual Contribution
Type 1	Summer	Weak (1.5–2.0 dB)	Moderate (4.0–5.5 dB)	High (6.0–7.5 dB)	5.0–7.5 dB(A)
	Winter	Weak (1.0–1.5 dB)	Minimal (1.5–2.0 dB)	Weak (2.0–2.8 dB)	2.0–3.0 dB(A)

Type 2	Summer	Weak (1.0–1.5 dB)	Extreme (9.0–11.0 dB)	Maximum (18.0–21.0 dB)	10.0–21.0 dB(A)
	Winter	Minimal (0.5–1.0 dB)	Weak (2.0–3.0 dB)	Weak (3.5–4.5 dB)	3.0–4.5 dB(A)
Type 3	All-Year	Constant (4.0–4.5 dB)	Constant (6.0–6.8 dB)	Constant (7.5–8.0 dB)	7.0–8.0 dB(A)

The mathematical analysis of the data proves that deciduous row-based screens (Type 2) possess a phenomenal capacity for absorbing noise from the tire contact patch in a foliated state (>1000 Hz), yet they remain structurally vulnerable. Conversely, evergreen structures (Type 3) guarantee a constant acoustic impedance of the environment (19.3 dB(A) total reduction), which defines them as a mandatory "structural skeleton" (minimum 30% of total biomass) for achieving year-round protection of public health in Sofia, Plovdiv, or any other large city.

6.3. Selection and Design Matrices

Vegetation selection for noise-mitigation purposes must not be arbitrary or driven solely by aesthetic considerations. It must be based on rigorous, objective biophysical criteria. In the course of this dissertation, a **Comprehensive Assessment Matrix** was constructed, integrating four key factors (Table 15):

1. **Acoustic Density:** This parameter is determined by the Leaf Area Index (LAI) and branch density. Species with large, thick, or pubescent leaves (such as *Tilia tomentosa*) have a proven higher sound-absorption coefficient due to increased friction of air particles within the leaf's boundary layer.
2. **Gas Resistance:** This represents the plant's ability to survive and function normally in an aggressive environment with high concentrations of nitrogen oxides (NO_x), carbon monoxide (CO), and fine particulate matter. This factor is critical for the economic efficiency of the investment, as it guarantees the longevity of the plantation.
3. **Edaphic Plasticity:** This evaluates salt tolerance (resulting from winter road chemical treatments) and the ability to thrive in compacted soils within an urban environment.
4. **Phenological Stability:** This accounts for the duration of the foliated period and the ability to maintain canopy structure during winter.

Building on data from Stoyanov (2021) and (Tsavkov & Yurukov, 2003), as well as my own field observations on the state of vegetation in Sofia, a selection of priority tree species was made.

The primary filter for selecting priority species in the presented matrix is their ecological plasticity and climatic adaptability. For the territory of Sofia, the selection is entirely aligned with the biological requirements of the taxa regarding thermal regimes and cold hardiness. The assortment used is limited to species whose genetic critical freezing point corresponds to the conditions of the Sofia Field. In his research, Widrlechner (1997) defines this range within USDA Zone 6 (from -17.8 °C to -23.3 °C), which guarantees the trouble-free overwintering of the taxa. Ignoring this microclimatic limit leads to defoliation or irreversible damage to the habitus, which directly compromises the density and protective function of the acoustic screen during the winter period.

Parallel to the climatic factor, when choosing species for the "front line" adjacent to the road, their gas resistance and ability to thrive under conditions of intense soil and atmospheric pollution are considered.

Applicability Matrix for Urban Planning Zones

Urban planning requires a strictly differentiated approach to vegetation selection. Applying a unified landscape model to territories with fundamentally different ecological parameters and functional objectives—such as industrial zones and historical centers—is scientifically inappropriate and professionally unjustified. In this regard, the regulatory framework, specifically Ordinance No. 7, defines specific requirements for setbacks, lighting, and visual comfort, which must be unconditionally met during the design process.

To overcome these spatial and ecological constraints, an applied model has been developed. Its objective is to directly guide landscape architects and engineers toward the correct taxonomic composition, depending on the functional purpose of the territory, in accordance with the General Urban Development Plan of Sofia Municipality (Table 16).

Table 16.

Selection Matrix for Priority Species in Zone 6

Botanical Name (Species)	Acoustic Efficiency (1–5)	Gas/Salt Resistance (1–5)	Growth Rate	Recommended Use (Construction Type & Specifics)
Picea abies	5	3	Medium	Type 1 (Background), Type 2. Provides high winter density and constant biomass in peripheral zones.
Thuja occidentalis	5	4	Fast	Type 2 (Hedge), Type 3 (Narrow screens). Excellent for dense, linear urban structures.
Taxus baccata	5	5	Slow	Type 2, Type 3. Extremely dense evergreen structure, tolerates radical pruning and deep shade.
× *Cupressocyparis leylandii*	5	5	Very Fast	Type 1, Type 2, Type 3. Rapid provision of year-round acoustic insulation. Perfect for commercial site perimeters.
Pinus nigra	4	5	Medium	Type 1 (Industrial and Mixed zones). Highly resistant to urban drought, poor soils, and winter salting.
Pseudotsuga menziesii	5	3	Fast	Type 1, Type 2. Deep canopy with large coniferous biomass, suitable for large-scale roadside screens.
Platanus × hispanica	4	5	Very Fast	Type 1 (Structural dominant). Large, dense leaves act as powerful sound reflectors and diffusers.
Tilia tomentosa	4	5	Fast	Type 2 (Street landscaping). Dense trichome (hair) layer on leaves traps large amounts of fine particulate matter (PM).
Acer platanoides	4	3	Fast	Type 1, Type 2. Forms a dense, mosaic canopy with a high Specific Leaf Area (SLA).
Acer campestre	4	5	Medium	Type 2, Type 3. Tolerates shaping. Critical for closing the middle and lower strata in underground infrastructure contexts.
Carpinus betulus	4	4	Medium	Type 2 (Shaped hedge). Partial winter screen – retains dry leaves until spring, reducing the phenological collapse.
Celtis occidentalis	4	5	Fast	Type 1, Type 2. Powerful root system and extreme tolerance to asphalt heat and heavy urban stress.
Fraxinus excelsior	3	5	Fast	Type 1 (Foreground – protective shield). Strong skeletal structure, resistant to mechanical damage and air currents.
Catalpa bignonioides	4	4	Fast	Type 1, Type 2. Huge leaf blades ensure excellent diffuse sound wave scattering during summer.

Gleditsia triacanthos	3	5	Fast	Type 1, Type 2. Thornless forms (f. *inermis*) recommended. Exceptional tolerance to dust and gases.
Robinia pseudoacacia	3	5	Very Fast	Type 1 (Suburban highway belts). Aggressive growth, strengthens terrain (suitable for slopes and landforms).
Quercus robur 'Fastigiata'	4	4	Slow	Type 2 (Spatially restricted zones). Narrow columnar canopy, suitable for medians between traffic lanes.
Populus nigra 'Italica'	3	4	Very Fast	Type 1. Suitable for the express construction of very high vertical screens, but has a short service life.
Styphnolobium japonicum	3	5	Fast	Type 2 (Urban highways). Extremely resistant to soil overheating and harmful emissions.
Betula pendula	2	2	Fast	Landscape accent only. Unsuitable for standalone noise mitigation due to its overly sparse canopy.
Aesculus hippocastanum	3	2	Medium	Limited to park environments. Not recommended for boulevards due to vulnerability to the leaf miner moth.

Table 17.

Application of Species by Urban Planning Zones

Urban Zone (Code)	Characteristics and Function	Recommended Species Composition (Extended Assortment)
R (Residential)	Predominantly residential areas. Aesthetics, safety (low allergenicity), acoustic comfort, and year-round isolation required.	Trees: *Picea pungens, Betula pendula, Acer pseudoplatanus, Tilia cordata, Sorbus aucuparia, Fraxinus excelsior, Carpinus betulus, Prunus serrulata* Shrubs: *Ligustrum vulgare, Spiraea japonica, Syringa vulgaris*
C (Central)	Business and old town centers (C2). High requirements for representativeness, canopy/root compactness, and heat-island resilience.	Trees: *Acer platanoides* 'Globosum', *Aesculus hippocastanum, Fraxinus pennsylvanica, Ginkgo biloba* (male specimens only), *Liquidambar styraciflua, Carpinus betulus* 'Fastigiata' Shrubs: *Taxus baccata, Buxus sempervirens, Ilex aquifolium*
M (Mixed-use)	Multi-functional zones with high traffic and commercial facilities. High resistance to dust, aerosol salts, and gases required.	Trees: *Acer campestre, Platanus × hispanica, Celtis occidentalis, Gleditsia triacanthos* f. *inermis, Pinus nigra* Shrubs: *Cupressocyparis leylandii* (for rapid buffers), *Prunus laurocerasus, Pyracantha coccinea*
P (Public/Institutional)	Healthcare, education. Extremely high requirements for sanitary protection, absence of toxic fruits, and release of phytoncides.	Trees: *Pinus sylvestris* (phytoncides), *Picea pungens* (winter shield), *Tilia tomentosa* (fragrance), *Liriodendron tulipifera, Abies alba* Shrubs: *Forsythia × intermedia, Chaenomeles japonica, Philadelphus coronarius*
I (Industrial)	Warehouses, logistics, and manufacturing. Focus on maximum filtration of Particulate Matter (PM), rapid growth, and large leaf biomass (SLA).	Trees: *Populus × berolinensis, Ulmus laevis, Robinia pseudoacacia, Elaeagnus angustifolia* (very strong dust filter), *Acer negundo, Quercus rubra* Shrubs: *Amorpha fruticosa, Cotinus coggygria, Hibiscus syriacus*
G (Green Spaces)	Parks, gardens, squares. Recreational function. Focus on biodiversity, visual noise masking, and poly-dominant structures.	Trees: Full range of native/indigenous species (*Fagus sylvatica, Quercus robur*) + decorative solitaires: *Malus floribunda, Magnolia × soulangeana, Larix decidua*

		Shrubs: *Cornus mas, Corylus avellana, Cotoneaster horizontalis*
S (Sports)	Areas for sports and attractions. Need for wind protection, provision of local shade, and resistance to mechanical damage.	Trees: *Populus nigra* 'Italica' (windbreaks), *Picea abies, Betula pendula, Ulmus minor, Acer platanoides* Shrubs: *Juniperus virginiana, Thuja occidentalis, Symphoricarpos albus*

Construction Matrix for Noise-Mitigation Screens

The presented synthetic matrix integrates the acoustic parameters of the environment with the biological potential of vegetative elements, defining the structural framework for the subsequent construction of specialized noise-mitigation types.

A synthesis and interdisciplinary connection between the morphological traits of vegetation, its biophysical capacity, and its specific role in the spatial structure of acoustic screens is shown in Table 28. The matrix has been developed as a design algorithm tailored to the needs of the urban environment (Table 17).

6.6. Supplementary Assortment for the Lower Stratum (0–1.5 m)

The introduction of a shrub and herbaceous understory is critically important for closing the "acoustic windows" at the base of the stems.

6.6.1. Shrubs for Noise Mitigation and Hedgerows

A serious and common oversight in modern landscape practice is the neglect of the lowest segment of green screens—the space from zero to one-and-a-half meters above the ground. If we aim for real sound attenuation and structural density (especially in the developed Type 1 and Type 3 constructions), the introduction of a shrub and herbaceous understory becomes critical. Fang and Ling (2003) explain this through the biophysical function of this ground stratum, which closes the so-called "acoustic windows." These zones of free sound transmission appear naturally at the base of tree stems as crowns rise with age.

Shrub Stratum: Functional Screening and Biomechanical Barrier

The selection of shrub species here is not driven by a search for decorative effect, but is based on clear morphological traits (primarily dense basal branching) and ecological plasticity in harsh urban conditions. The selected assortment is divided into three distinct groups:

- **Dense-structural species (forming masses):** This includes species such as *Ligustrum vulgare*, *Ligustrum ovalifolium*, *Spiraea x vanhouttei*, and *Symphoricarpos albus*. Their main advantage is high regenerative capacity, which allows them to withstand intensive pruning and form an extremely dense habitus. Experiments by Fan et al. (2010) on the frequency attenuation range prove something very important: the high density of shrubs (especially in small-leaved taxa like *Ligustrum*) plays a decisive role in capturing and scattering the medium and high frequencies of traffic noise.
- **Protective-barrier (thorny) species:** Representatives such as *Berberis thunbergii*, *Crataegus* spp., and *Rosa* spp. These plants add a purely mechanical, security function to acoustic diffraction. Since they form thorny and impenetrable masses, they practically stop unauthorized pedestrian crossing toward the roadway.
- **Halophytic taxa (salt-tolerant):** Species such as *Caragana arborescens* and *Cotoneaster lucidus*. Placing them in the front line, in immediate proximity to the curb, has serious scientific support. As noted by Tsavkov and Yurukov (2003), these plants possess remarkable endurance to high salt concentrations in the soil and to the aggressive chemical aerosols used for street cleaning during the winter months.

Table 18.

Generalized Matrix for Designing/Constructing Vegetative Noise-Mitigation Screens

Taxa Category by Functional Feature	Representative Species (Reference Assortment)	Spatial-Acoustic Function in Screen Structure	Seasonal Screening Capacity	Landscape Planning Scope (Application)
I. Skeletal / Fast-growing (Vertical dominants)	*Populus x berolinensis*, *Ulmus laevis*, *Salix alba*, *Robinia pseudoacacia*, *Acer negundo*, *Platanus x hispanica*	Accelerated vertical screening; formation of a primary diffraction profile at heights > 5–8 m.	Optimal (Summer) / Reduced (Winter)	Periphery of M-zones (Mixed multi-functional zones), Industrial territories (I).
II. Dense / Noise-absorbing (Core)	*Tilia cordata*, *Acer platanoides*, *Fraxinus excelsior*, *Carpinus betulus*, *Quercus rubra*, *Catalpa bignonioides*	Primary absorption and multiple scattering of sound energy through large leaf surface (SLA/LAI) and dense canopy.	High (Vegetation period)	Residential zones (R), Central urban parts (C).
III. Evergreen / Permanent (Insulating)	*Picea pungens*, *Pinus nigra*, *Thuja occidentalis*, *Cupressocyparis leylandii*, *Taxus baccata*, *Picea abies*	Provision of continuous acoustic impedance throughout the year; filling "winter deficits" and blocking reverberation.	Year-round (Maximum in winter relative to deciduous)	Integration into all construction types as a stabilizing element. Commercial zones and parking lots.
IV. Decorative / Ajour (Visual correctors)	*Betula pendula*, *Sorbus aucuparia*, *Prunus cerasifera*, *Koelreuteria paniculata*, *Ginkgo biloba*, *Acer pseudoplatanus f. purpureum*	Psycho-acoustic masking (Visual Masking); provision of aeration and visual permeability in pedestrian access zones.	Medium / Psychological reduction	Park territories (G), Recreational pockets, Pedestrian alleys.
V. Basal (Shrub) / Understory (Ground isolators)	*Ligustrum vulgare*, *Spiraea x vanhouttei*, *Berberis thunbergii*, *Prunus laurocerasus*, *Viburnum opulus*, *Pyracantha coccinea*, *Cornus alba*	"Sealing" the ground-level acoustic windows (0–2 m); elimination of sound translation beneath crowns. Noise absorption directly from tires.	High (in dense planting, especially with evergreen taxa)	Type 1 and Type 3 constructions; linear street plantings; boulevard contact zones.

6.6.2. Floral Stratum: Psycho-Acoustic Interference (Visual Masking)

From the perspective of pure physics, herbaceous and floral vegetation cannot directly reduce sound pressure levels in decibels, as they lack the necessary biomass and volume. Attenborough (1988) explicitly notes this limitation; however, the presence of these species in the urban environment is fully justified. It is based on the concept of Yang et al. (2011) regarding the psychological reduction of noise.

The integration of floral parterres at the lowest level helps to optimize the environment in three ways:

1. **Acoustic Absorption at Ground Level (Ground Effect):** Unlike asphalt and concrete, which are typical acoustic mirrors that amplify noise through reflection, living soil covered with vegetation acts as a natural porous absorber. The foliage in the zone up to 30 cm alters the ground's acoustic impedance. Attenborough (1988) points out that this captures a significant portion of the sound energy moving low over the surface, primarily in the high-frequency spectrum. Furthermore, findings by Aylor (1972) and Horoshenkov et al. (2013) demonstrate that plants with large leaf blades (such as *Hosta* spp.) scatter reflected waves through micro-diffraction. Since their biometric dimensions match the wavelength of high-frequency sound, they act as excellent diffusers.
2. **Generation of Positive Biophony (Soundscape approach):** Modern urban acoustics relies not only on the physical isolation of noise but also on the introduction of so-called "masking sounds" from nature. The use of melliferous and entomophilous species such as *Salvia splendens*, *Lavandula angustifolia*, and various representatives of the *Asteraceae* family attracts birds and insects. As research by De Coensel et al. (2011) proves, buzzing and birdsong, combined with the natural rustling of leaves in the wind, create a pleasant soundscape. This acts as a calming influence and successfully masks the low-frequency rumble of vehicular traffic.

Alongside this, studies in environmental psychology published by Yang et al. (2011) prove the power of visual masking. When we hide the source of annoyance behind beautiful landscape elements, we effectively alter human subjective perception. Color patches in the foreground distract attention and have been proven to reduce stress levels and the sense of noise discomfort. To achieve this visual distraction in Sofia, Shtilyanova (2005) recommends selecting species that combine a strong decorative effect with resilience to urban pressure. This group includes:

- **Annual taxa (for intensive color):** *Tagetes erecta*, *Petunia x hybrida*, *Salvia splendens*.
- **Perennial taxa (for sustainable structural groups):** *Hosta* spp. (suitable for shaded areas under trees), *Hemerocallis* spp., *Sedum spectabile*.

6.6.3. Acoustic Efficiency of "Green Tracks"

The use of specialized vegetation (e.g., drought-resistant grass mixtures) finds its most effective engineering and ecological implementation in rail transport. The technological line of green tram tracks, tested on the Sofia "Macedonia" Boulevard, is based on extensive global practice. In their research, Van Renterghem and Botteldooren (2014) established that replacing traditional stone ballast with sedum or living grass entirely changes the spectral composition of the noise. Frequencies around 1000 Hz are attenuated most noticeably—precisely those to which the human ear is most sensitive and which it perceives as the most aggressive.

Studies by Cholakov (2018) during the reconstruction of Sofia's tram lines demonstrate important additional benefits: effective capture of fine particulate matter (PM) at the source and a noticeable reduction in vibrations that threaten the foundations of adjacent historic buildings.

The soil substrate and vegetation cover have a high sound absorption coefficient ($\alpha > 0.5$). This activates the so-called "soft ground effect." Direct measurements on Macedonia Blvd. recorded a peak level drop of 4.2 dB(A) compared to a standard open track. This result coincides perfectly with the data of Van Renterghem and Botteldooren (2014), who report an average efficiency between 3 and 5 dB(A) for analogous projects in cities such as Ghent and Rotterdam (Table 18).

Table 18.

Comparative Effectiveness of Tram Track Surfaces

Track Construction Type	Acoustic Impedance	Reflection	Reduction vs. Concrete	Efficiency Rating
Concrete Slab	High (Hard)	> 90% (Strong)	Reference (0 dB(A))	Low. Amplifies noise in the urban canyon.
Ballast (Stone)	Medium	60–70% (Partial scattering)	~ 1–2 dB(A)	Moderate. Good vibration absorption, but retains dust.
Green Tram (Grass/Sedum)	Low (Soft)	< 30% (Weak)	3 – 5 dB(A)	High. Absorption + excellent ecological effect.

The analysis of the results from the study of the "Linear Park" on Macedonia Boulevard allows for an important generalization: effective noise mitigation is never the result of an isolated barrier, but is instead due to the depth and spatial structure of the green belt.

If we compare our data with the French experience—specifically the famous *Promenade Plantée* project in Paris—a clear pattern emerges. When vegetation is correctly combined with a pedestrian zone and distance from traffic is ensured, the subjective sensation of noise pressure decreases radically. Under Sofia's conditions, the "Linear Park" model on Macedonia Blvd. proves in practice that even with the persistence of heavy traffic, the introduction of a "green buffer" (composed of four rows of trees—two lateral and two central—several parallel rows of hedges, and a grassed tram track) creates a true island of acoustic comfort for pedestrians. Field measurements confirm a noise drop to a fully tolerable 60–62 dB(A) in the pedestrian alley zone during the summer period, when the vegetation is fully foliated.

7. CONCLUSIONS

The theoretical research, instrumental monitoring within the Sofia agglomeration, and the subsequent comparative analysis of dendrological models conducted within this study provide the basis for formulating the following conclusions:

The proposed comprehensive methodology ensures a high degree of scientific reliability and representativeness of empirical data by achieving synergy between objective instrumental monitoring and in-depth expert interpretation.

7.1. Scientific-Theoretical Conclusions Regarding the Mechanism of Action

1. **Physico-Biological Mechanism of Phyto-Screens:** It has been established that vegetation belts do not function solely as a linear physical barrier analogous to conventional engineering structures. They represent a complex, dynamic system for energy dissipation. Their effectiveness is the result of synergy between three physical processes: absorption of sound waves by the porous structure of bark, leaves, and soil; diffraction (bending) of the wave around the mass; and multiple internal reflection within the crowns. It is proven that the "softness" of the plant tissue is a critical factor for the absorption of the high-

frequency spectrum (above 1000 Hz) generated by tire friction, while the density of tree trunks is responsible for reducing low-frequency vibrations.

2. **Structural Dependency and the Imperative of Biodiversity:** Monoculture plantations demonstrate limited effectiveness and higher vulnerability. The research has categorically shown that poly-dominant structures increase the acoustic capacity of the screen by up to 15–20%. Diverse leaf morphology creates a multi-layered filter. However, the vertical structure remains a critical factor: trees with high-lifted crowns and exposed trunks allow noise to pass unhindered in the ground layer (0–2 m). Without the presence of a dense shrub understory to close this "acoustic gap," the noise-mitigation effect remains primarily psychological.
3. **Phenological Paradox and Seasonal Dynamics of Protection:** Empirical data from Sofia revealed a drastic dependence of effectiveness on the phenological phase. In deciduous species (*Tilia*, *Acer*, *Fraxinus*), a collapse in noise-mitigation capacity of up to 60–70% is observed during the winter period. This fact necessitates a review of current practices and scientifically justifies the necessity of mandatorily including evergreen species (*Picea*, *Cupressus*, *Thuja*) in a ratio of no less than 30% of the total biomass volume.

7.2. Practical Conclusions from Applied Case Studies (Kazichene, Botevgrad, Technopolis)

1. **Spatial Imperative and Functional Zoning:** The "proximal protection" rule is confirmed. A green barrier realizes its maximum potential when situated at a distance of 6.0–10.0 meters from the source. The analysis of the "Kazichene" case showed that in large park territories, internal micro-zoning is necessary, whereby sensitive areas (playgrounds) are protected with local screens (Type 3) to compensate for noise from the internal path network.
2. **Effectiveness of the "Green Shield" in Residential Environments:** The design solution for the "Botevgrad" Residential Complex proved that a multi-tiered structure is required to achieve real acoustic comfort in the "Rs" (Residential) zone. The use of over 2,500 *Prunus laurocerasus* hedging units in combination with tall deciduous trees creates a dense barrier that simultaneously blocks tire noise and aerodynamic traffic noise.
3. **Economic and Spatial Optimization via Vertical Landscaping:** The "Technopolis" case (with 512 linear meters of vertical landscaping implemented) demonstrates that in industrial zones (M-zones), biological screens are the most effective economic alternative. A combination of vertical walls and fast-growing evergreen species (× *Cupressocyparis leylandii*) achieves maximum protection with minimal land use footprint.

8. LIST OF SCIENTIFIC AND APPLIED CONTRIBUTIONS

Scientific Contributions (Theoretical):

- **Definition of the Physico-Biological Mechanism:** It has been scientifically proven that phyto-screens function as a complex system for sound energy dissipation through a synergy of absorption, diffraction, and micro-reverberation.
- **Proof of Seasonal (Phenological) Dynamics:** The "phenological collapse" in acoustic efficiency in purely deciduous arrays during the winter period has been quantitatively measured and proven.
- **Development of an Acoustic Transfer Mathematical Model:** A model has been created for the quantitative calculation of Insertion Loss.

Scientific-Applied Contributions (Practical):

- **Creation of an Original Structural Typology:** Three spatial-functional models of phyto-screens have been developed and validated (Type 1: Aerodynamic, Type 2: Staggered, Type 3: Combined).
- **Construction of a Comprehensive Selection Matrix:** A specialized matrix has been developed for the selection of priority tree and shrub species for Zone 6.
- **Approbation in Real Urban Environments:** The technical-economic and landscape effectiveness of biological solutions has been proven at critical infrastructure sites (Technopolis Commercial Complex, Botevgrad Residential Complex).

9. POTENTIAL USERS OF THE DISSERTATION

This work has applications in university practice and can serve as a foundation for the education of students in landscape architecture. Furthermore, it can be utilized as a basis for creating practical guidelines for the design of green spaces in urban environments. The work establishes a reliable foundation that is directly applicable to contemporary landscape design practice.

10. DIRECTIONS FOR FUTURE RESEARCH

Possible follow-up and in-depth research could focus on:

- In-depth study of vegetation construction in intermediate green spaces on sloped terrains.
- In-depth study of vegetation construction in low-rise residential areas.
- In-depth study of vegetation construction in high-rise residential areas.
- Expansion and upgrading of the taxonomic matrix.

11. LIST OF PUBLICATIONS RELATED TO THE DISSERTATION

1. Grozeva, M. P. (2023). An Optimised Design for Transport Noise Pollution Reduction in the Children's Area and Recreation Spots. *Agricultural Sciences*, 15(37), 12-19. DOI: 10.22620/agrisci.2023.37.002
2. Grozeva, M. P. (2023). Macedonia Boulevard Linear Park Design for Reduced Transport Noise Pollution. *Agricultural Sciences*, 15(37), 20-29. DOI: 10.22620/agrisci.2023.37.003

12. SUMMARY

TYPOLOGY AND METHODS FOR NOISE PROTECTION THROUGH THE USE OF GREEN VEGETATION IN URBAN ENVIRONMENTS

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The current dissertation addresses the critical issue of urban traffic noise pollution within the Sofia agglomeration by proposing sustainable, nature-based solutions. While traditional urban planning relies heavily on artificial noise barriers, this research explores and validates the largely untapped potential of vegetative noise screens (phyto-screens).

The main objective of the study is to develop a scientifically grounded methodology and a spatial-functional typology for the design of highly efficient green noise barriers. The research applied a complex methodology involving systematic in-situ acoustic monitoring across 19 critical urban locations, comparative seasonal analysis (summer versus winter phenological states), and specific experimental case studies using high-precision digital sonometers.

The results empirically prove the physical and biological mechanisms of sound attenuation through plant biomass. Phyto-screens operate as a complex system for sound energy dissipation through the synergy of acoustic absorption (via foliage and substrate), diffraction around canopies, and micro-reverberation. A critical finding is the

measurement of the "phenological collapse"—a drastic reduction in the noise-shielding efficiency of purely deciduous plant belts during the winter season, reaching a 60–70% decline. This validates the necessity of integrating at least 30–50% evergreen taxa in urban green infrastructure.

A major scientific contribution of this work is the development of the Mathematical Model of Acoustic Transfer, which differentiates and quantifies the total noise attenuation (Insertion Loss) based on geometric divergence, vegetative absorption, and soil impedance. Practically, the dissertation introduces an original Constructive Typology of green barriers (Aerodynamic, Quincunx, and Combined types) and a comprehensive selection matrix for woody and shrub species suitable for Hardiness Zone 6.

The theoretical models were successfully validated through real-world implementation projects, such as the "Green Tram" technology on Macedonia Blvd., and multi-layered evergreen buffers in residential and commercial zones, proving that bio-engineered vegetative barriers serve as a highly effective and economically viable alternative to artificial noise walls.