

# Influence of Spatial Morphology on Acoustical Performance in Mosque Prayer Halls: A Comparative Simulation Study

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**Abstract:** This study investigates the influence of spatial morphology on the acoustic performance of mosque prayer halls through a comparative simulation-based analysis of five contemporary mosque typologies in the Kurdistan Region of Iraq. Acoustic performance was evaluated under full-occupancy conditions using geometric ray-tracing and particle-based simulations. Reverberation time ( $RT_{60}$ ), sound distribution patterns, and sound-focusing behavior were assessed using the Sabine, Norris–Eyring, and Millington–Sette models. The findings demonstrate that acoustic performance is strongly influenced by architectural geometry. Prayer halls characterized by large continuous interior volumes and dominant central domes were associated with excessive reverberation, low-frequency sound accumulation, and localized sound-focusing effects. In contrast, layouts incorporating distributed dome systems and greater structural articulation exhibited more balanced sound distribution and improved reverberation control. The results further indicate that under identical material and occupancy conditions spatial morphology plays a critical role in shaping acoustic conditions. This study highlights the importance of integrating acoustic considerations during the early stages of mosque design and suggests that architectural form should be treated as a primary acoustic design parameter rather than relying solely on post-construction acoustic treatments. Future studies should prioritize empirical field measurements to further validate these computational models across a broader range of architectural typologies.

**Keywords:** Mosque Acoustic Performance; Reverberation Time; Mosque Geometry; Spatial Morphology; Computational Modeling; Acoustic Simulation; Speech Intelligibility.

## 1. Introduction

Religious buildings such as mosques and churches are important cultural and spiritual centers in communities because of their connection to individual conviction and community worship [1]. Such spaces occupy a unique role, providing a locus for personal contemplation whilst encouraging community [1,2]. The architectural configuration of such spaces plays a pivotal role in shaping the spiritual experience, in which acoustic performance is essential to achieving a sense of sacredness and tranquility [3,4]. Well-designed acoustic environments contribute to speech intelligibility, auditory comfort, and the elimination of disruptive sound phenomena such as echoes and flutter echoes, thereby enhancing the overall worship experience [5].

When a sound is produced in a room, numerous processes occur almost instantaneously. The room's boundaries cause sound waves to reflect repeatedly, preventing the immediate formation of a uniform sound field, especially in religious buildings [6]. Over time, this sound field diminishes as the room's materials absorb the sound energy. The rate at which the sound energy decreases depends on the absorption properties of the reflective surfaces. Additionally, the duration required for the sound intensity to decrease by 60 decibels is known as the "reverberation time" [7], as illustrated in Figure 1.

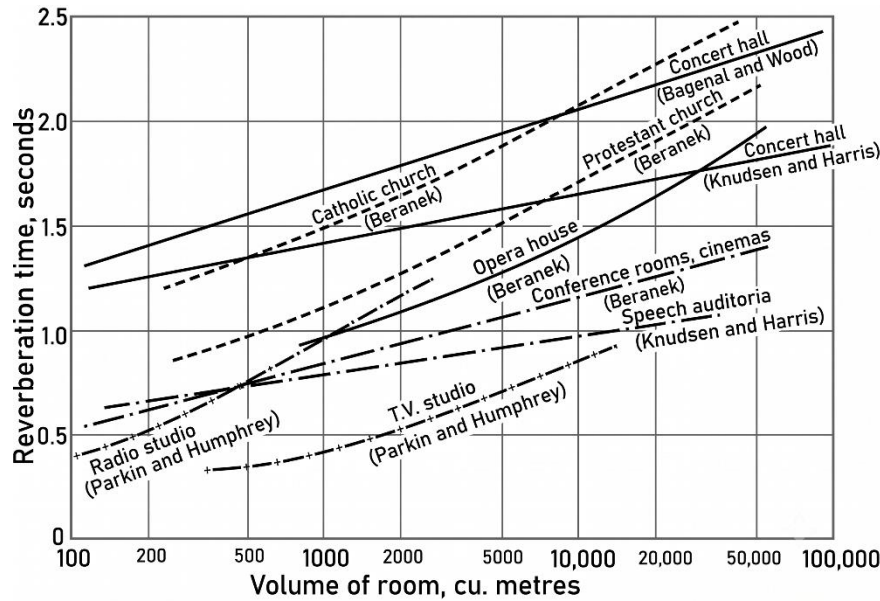


Figure 1: Reverberation time (RT) values across various space types. For mosques, the optimal RT range is typically between 0.6 and 1.2 seconds, ensuring adequate speech intelligibility and acoustic comfort [8].

In Erbil, a city located in the Kurdistan Region of Iraq, newly built mosques are being evaluated for their acoustic performance. Many of these mosques exhibit ongoing problems with excessive reverberation time ( $> 2.0$ s at 500Hz) [4], dome-related sound focusing, and poor speech intelligibility despite the use of sound reinforcement systems [4]. The inherent issues with the geometry and material selection of the prayer halls preclude any solutions other than electro-acoustic ones. Although some studies have documented adverse acoustics in individual mosques, very few provide a controlled comparative analysis of the acoustics of mosque prayer halls with different geometries (round vs. rectangular), representative contemporary mosque typologies, people (occupancy), and materials used [9]. This lack of comparative data is especially concerning in the Kurdistan Region, where there is a rapidly increasing demand for mosque construction and systematic acoustic evaluations are rarely conducted [4].

This study, in an evidence-based manner, compares five different mosque geometries (circular, large rectangular, and pillared) to support the development of acoustic guidelines for mosque design in the Kurdistan Region. It is being undertaken to determine whether or not acoustical issues are present due to architectural design decisions. Acoustical modeling will be performed using computer software to visualize architectural choices, produce renderings, and predict the acoustical effects of those choices. Acoustical modeling will allow prediction of acoustical problems caused by geometry prior to any physical construction [10]. [11] such as low-frequency resonance from large interior volumes or acoustic concentration under very large domes within the structure. By examining each of these typologies under identical conditions of full occupancy, it is possible to explore how, in the physical world, architecture does not always behave as predicted by theoretical acoustics. Specifically, this research will explore how much greater reverberation is produced in very large, continuous open spaces and how well each typology provides supporting conditions for clear, unamplified human speech.

The premise for these research findings is that a large central dome configuration has lower acoustic performance because of uncontrolled reverberation and long-term echoes when compared to the segmented structure of geometrically segmented spaces (e.g. large structural support pillars or multicellular domes), which will act as natural acoustic “regulators”, thus due to having similar materials and occupancy, geometrically segmented spaces can avoid excessive low-frequency resonances and

create homogeneous sound distribution and achieve the required  $RT_{60}$  targets for optimal speech intelligibility.

## 2. Literature Review

### 2.1 Studies on Acoustic Function and Space Utility in Mosques

Recent literature highlights that modern mosques serve complex functions beyond prayer, which places higher demands on their acoustic environments. [1] examined the expanding role of mosques as centers of education and social engagement, while [13] investigated the modern mosque as a "hybrid space" that accommodates both worship and tourism. Moreover [2] demonstrated that the built environment directly dictates an individual's spiritual experience, researchers have increasingly sought to quantify how acoustic failures disrupt this utility. To evaluate these spaces, studies consistently rely on established metrics. [15] investigated speech intelligibility in large spaces, concluding that the Speech Transmission Index (STI) is a highly applicable metric for expansive assembly halls. However, in physical case studies, contemporary designs frequently fail these metrics. [5] conducted on-site assessments of mosque acoustics. They found that newly constructed prayer halls consistently exceed the recommended reverberation time ( $RT_{60}$ ) due to their large enclosed volumes and reliance on highly reflective modern materials, ultimately degrading auditory comfort.

### 2.2 Research on Architectural Geometry and Dome Configurations

There has been considerable research exploring the relationship between the acoustics and geometry of a space, including the work of [11] on how modern building styles in Sulaymaniyah changed the average proportions of the mosques relative to historic precedents. In addition, a study performed by [16] showed that with respect to dome structures, rectangular plans provide a more uniform distribution of acoustical energy than either centrally or circularly oriented plan forms.

Moreover [9] drawn a particular attention to the acoustic behavior of ceilings, tested different dome shapes, determining that large hemispherical and central domes serve as acoustic reflectors, converging sound paths and thereby greatly increasing the overall reverberation time and the low-frequency peak of resonance. [16], conversely, use multi-dome configurations that break the paths of reflection and, as such, reduce the local defect of focusing. Beyond ceilings, localized morphology also plays a role, with [6] analyzing the shape of the Mihrab (prayer niche), revealing that its specific geometry results in markedly different behavior in the directivity and sound quality at the front of the hall. Other recent work has begun to draw more explicit links between form and the phenomenology of the hall itself; [10], for example, note that the very same morphological choices have simultaneous consequences for variables such as comfort and daylighting performance.

### 2.3 Computational Simulation methodologies in Recent Literature

To analyze such complex geometries without incurring construction costs, investigations in recent years have increasingly relied on physical modeling. [20] created frameworks for parametrically exploring the acoustical performance of large prayer halls using ray tracing. [12] make use of acoustic design simulations to optimize a square-plan mosque. Their study demonstrates that a parametric remodeling of ceiling forms and the implementation of fair-weighted acoustic treatment modifications yielded clear gains in RT spectra at the expense of the architect's vision.

The fidelity of these simulation tools has also been attended to [17] that ran the Salman-ITB mosque in Ecotect and confirmed that when absorption coefficients and occupancy assumptions are entered correctly, the simulation results closely match physical measurements. Researchers are studying these simulations for sound systems as well; [24, 25]. used an optimization framework to simulate zoned

audio distribution and active sound directivity, respectively, and confirmed that technological feedback could attenuate the late-energy reflections from the expansive marble surface.

## 2.4 Environmental Factors and Regional Case Studies

There are many critical aspects of the physical environment, so many researchers have conducted an investigation of potential high ambient noise levels and humidity and their impacts on the acoustics of reflective surface treatment in a new prayer space in the city of Makassar, Indonesia [21,22]. In addition, [23] studied the historical Grand Mosque of Yogyakarta, which uses traditional Javanese building materials that absorb early reflections, yielding better acoustic results than newer buildings. In their evaluation of a university mosque in Konya, Kaygısız, Semerci, and Tuna [14] emphasized the need for site-specific analysis of mosque acoustics. Furthermore, numerous localized case studies conducted in the Kurdistan region of Iraq have identified significant architectural deficiencies. Specifically, [4] evaluated the acoustics of recent mosque buildings in Erbil using software programs (ODEON) to model Dayk and the Altun mosque under different occupancy scenarios. Their results confirmed the poor overall acoustic quality of modern prayer facilities, most of which have poor acoustic characteristics because architects often do not consider acoustics when designing new buildings and have therefore created spaces that rely on heavy use of electro-acoustic amplification to make them functional.

## 2.5 Research Gap and Objectives

Although there is extensive literature on simulation methodologies [12] and regional acoustic failures [4], few studies systematically and quantitatively evaluate contemporary mosque typologies. Most computational evaluations are conducted in limited cases, so there is little to reference to determine the comparative functions of plan types when volume, function, and materials are controlled [22]. In this effort, however, the gap is bridged by using a common analytical framework to evaluate the five most recently built Friday mosques in Erbil. This research seeks to provide geometry-based indicators for acoustic design to avoid structural acoustic failures identified in previous studies by correlating specific geometries with simulated RT spectra, sound ray distributions, and localized focal points.

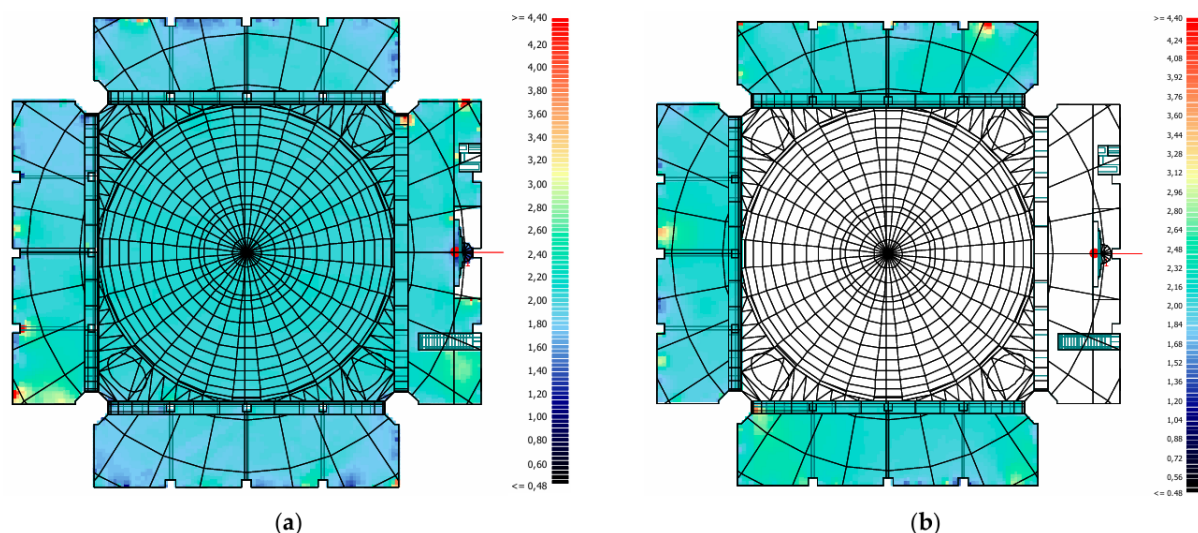


Figure 2: Friday Prayer Activity Reverberation Time (T30) Parameter Grid Calculation (1000 Hz) [12].

## 3. Methodology

The comparative simulation-based method used in this research employed Autodesk Ecotect Analysis, which utilizes geometric ray-tracing to analyze large-volume and curved-roofed mosques, thereby

allowing the evaluation of how well the proposed geometries will perform acoustically. With this software, it is possible to visualize sound rays as they spread through an enclosed space, interact with particles within it, and decay over time. Additionally, using Autodesk Ecotect Analysis Software, we evaluate reverberation, sound focusing, echo formation, and the even distribution of acoustics across three-dimensional building spaces made of different materials. However, all have the same absorption coefficients, as it is a very useful tool for acoustical simulation [17] and [5]. To accurately determine the reverberation time ( $RT_{60}$ ) within the mosque interior, the Norris-Eyring equation was applied (Equation 1). This formula yields more precise predictions for enclosures with highly absorbent materials, making it the optimal method for analyzing these architectural environments.

$$(1) \quad RT_{60} = \frac{0.161 \times V}{-S \ln(1 - \bar{\alpha})}$$

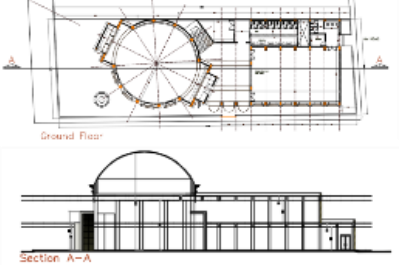
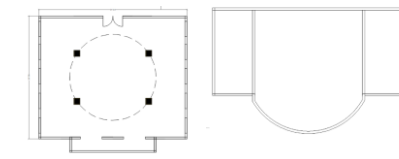

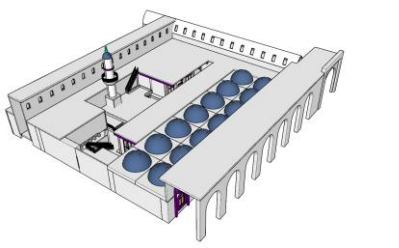
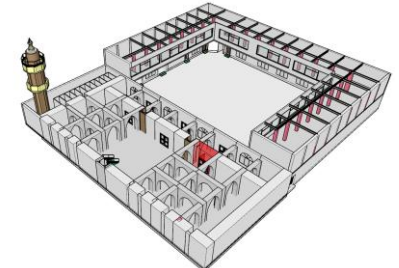
Equation 1  $RT_{60}$  reverberation time [17].

Where  $V$  is the volume ( $m^3$ ),  $S$  is the total surface area ( $m^2$ ), and  $\bar{\alpha}$  is the average absorption coefficient. This method was selected over the Sabine equation due to its improved accuracy in spaces with higher absorption levels (total absorption = 12–28 units), with reported errors below 4.2% compared to 8–12% for the Sabine model [17].

In Erbil, the Kurdistan Region–Iraq, five mosques have been chosen for the case studies to reflect geometric configurations with equivalent functional attributes. The Haidar Agha Mosque is a circular building with a quarter dome; its gross volume is 2903 cubic meters, and it can accommodate up to 400 worshippers. Next, the Altun Mosque has been designed in the traditional rectangular format with a single central dome; its gross volume is 10,629 cubic meters and it can accommodate a maximum of 950 worshippers. The third mosque, Firdaws Mosque, consists of a rectangular hall with a hemispherical dome, having a gross volume of 7420 cubic meters and capable of accommodating 550 worshippers.

The fourth mosque is Haji Dawood Mosque, which has been designed to be rectangular but contains a unique roof system with fourteen small domes. Haji Dawood Mosque has a gross volume of 2520 cubic meters and accommodates 350 worshippers. Finally, Koya Grand Mosque has an overall rectangular layout, with a central dome and various other elements supporting the domes throughout the interior. Its gross volume is 2008 cubic meters, and it can accommodate up to 540 worshippers. All five mosques meet the same criteria for daily use on Friday, are prepared to accommodate 100% capacity, and share similar interior finishes. However, the geometric configuration and design of their domes will be the independent variables determining the mosques' acoustic performance levels, as outlined in Table 1.

Table 1: Physical and Acoustic Characteristics of the Selected Mosques

Mosque Name	Prayer Hall Geometry Type	Volume (m <sup>3</sup> )	Capacity (Worshippers)	Dome Configuration	Image
<b>Haidar Agha Mosque</b>	Circular Plan	2903	400	Quarter Dome	
<b>Altun Mosque</b>	Rectangular Plan	10,629	950	Central Dome	
<b>Firdaws Mosque</b>	Rectangular Plan	7,420	550	Hemispherical Dome	
<b>Haji Dawood Mosque</b>	Rectangular Plan	2,520	350	Multi-Dome (14 domes)	
<b>Koya Grand Mosque</b>	Rectangular Plan	2,008	540	Central Dome with Pillars	

The interior finishes were chosen according to recognized standards for sound absorption in the given finishes (carpet, gypsum plaster, glass, and wood). The absorption coefficient ( $\alpha$ ) of the red carpet was between 0.30 and 0.60; gypsum plaster had an absorption coefficient of 0.04 to 0.07; glass was between 0.03 and 0.05; and wood panels had an absorption coefficient of approximately 0.30. Therefore, each of the interior finishes had frequency-dependent absorption coefficients across standard octave bands

[125 Hz, 250 Hz, 500 Hz, 1 kHz, 2 kHz and 4 kHz] in order to produce an accurate prediction of the acoustics. This was particularly important for the speech-centric frequencies. The acoustics were analyzed under full occupancy using sound simulations, with the sound source located in the Imam area and the receivers in different areas of the prayer hall. The ultimate acoustic performance was determined by evaluating the following key areas:  $RT_{60}$ , sound ray propagation, sound particle distribution, echo formation, and spatial uniformity. To evaluate echo characteristics, both analysis arrangements and time-of-arrival to the reception point were used. For example, echoes occurring after 50 ms or longer could interfere with speech intelligibility. To locate areas that would provide sound focusing within the prayer hall, particle density maps were created, and locations with particle densities at least three times the average energy concentration were considered significant. Spatial uniformity was assessed by analyzing receiver points to quantify the consistency of the acoustic environment within each mosque.

The accuracy of the model was confirmed through a variety of verification methods. Similarities between the Norris–Eyring prediction and published experimental data showed an error of less than 4.2% ( $\pm$ ) in frequency bands. Convergence tests with different numbers of particles (i.e., 500,000 to 1,000,000) yielded stable RT values that varied by less than 2%, indicating adequate resolution for the simulations. Material sensitivity tests showed that  $\pm 10\%$  variations in absorption coefficients resulted in RT changes of  $< 5\%$ , demonstrating the robustness of the model. Data processing used standard methods for acoustic analysis, such that  $RT_{60}$  values were obtained from energy decay curves via linear regression over the decay range of 5–35dB, in accordance with [19]. All results were analyzed according to recommended criteria for mosque design. In particular, this included assessing whether the acoustical performance falls within the optimal  $RT_{60}$  range (0.6–1.2 seconds) for speech.

## 4. Results

### 4.1 Volumetric Analysis and Acoustic Performance

To understand the baseline acoustic behavior of a given mosque, computational simulation studies were conducted to evaluate the physical Reverberation Time ( $RT_{60}$ ) at the critical frequency range for human speech, 500 Hz, against the mathematical optimum  $RT_{60}$  for that mosque volume. Additionally, a capacity analysis was completed, along with a physical measure of seat-to-volume ratio (volume/number), to evaluate overall acoustic density and determine how much of a difference in acoustic density exists due to variations in architectural proportions and form.

#### 4.1.1 Haidar Agha Mosque (Circular Plan with Quarter Dome)

The Haidar Agha Mosque Acoustic Model indicates that there is a large deviation between its mathematically calculated  $RT_{60}$  target of 0.94 seconds and an  $RT_{60}$  value of 6.02 seconds for the 500 Hz speech band (see Table 2). The material used in the space has sufficient absorption, but there is still evidence of excessive low-frequency resonances, with the maximum occurring at 125 Hz (13.92 s). Additionally, the ray tracing results (see Figures 3 & 4) show that the quarter-dome and circular geometries produce strong centripetal reflections that concentrate acoustic energy and create localized masking effects in the vicinity of the Imam. The results suggest that the continuing curves of these spaces create acoustic amplifiers, producing non-uniform sound fields and communication difficulties due to the equal contribution from all finishes.

Table 2: statistical acoustic RT for Haidar Agha Mosque

FREQ.	TOTAL ABSORP.	SABINE RT (60)	NOR-ER RT (60)	MIL-SE RT (60)
63 Hz	16.085	9.79	13.87	14.77
125 Hz	15.852	9.75	13.92	4.65
250 Hz	15.571	4.65	5.42	3.32
500 Hz	15.223	5.04	6.02	3.75
1 kHz	14.784	4.71	5.53	3.74
2 kHz	14.204	3.52	3.93	3.05
4 kHz	13.395	2.37	2.54	2.2
8 kHz	12.156	0.97	1	0.95
16 kHz	9.909	0.75	0.76	0.74

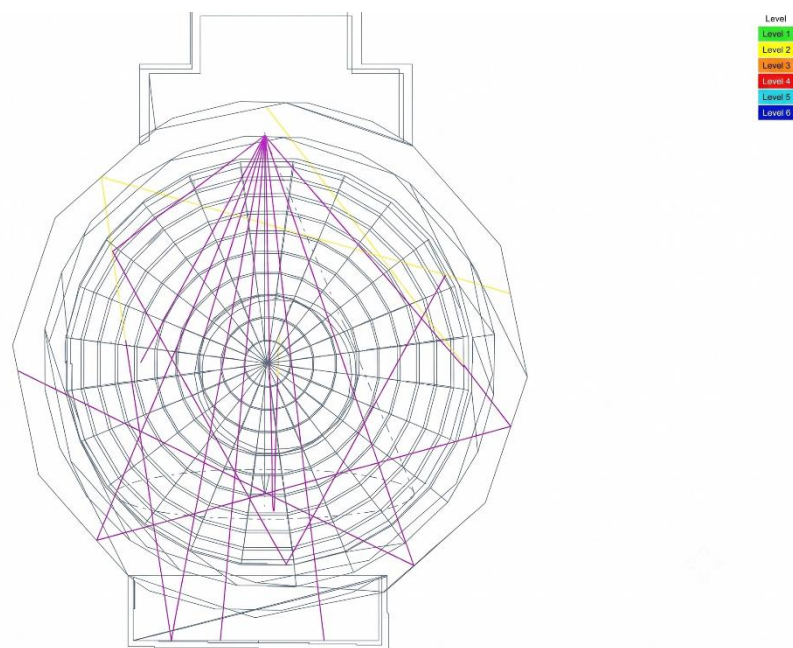


Figure 3. Plan-view simulation of reflected sound rays in the prayer hall of Haidar Agha Mosque.

Simulation and analysis of the time delay in the main prayer hall of Haidar Agha Mosque, measured in milliseconds, are presented in the figure below:

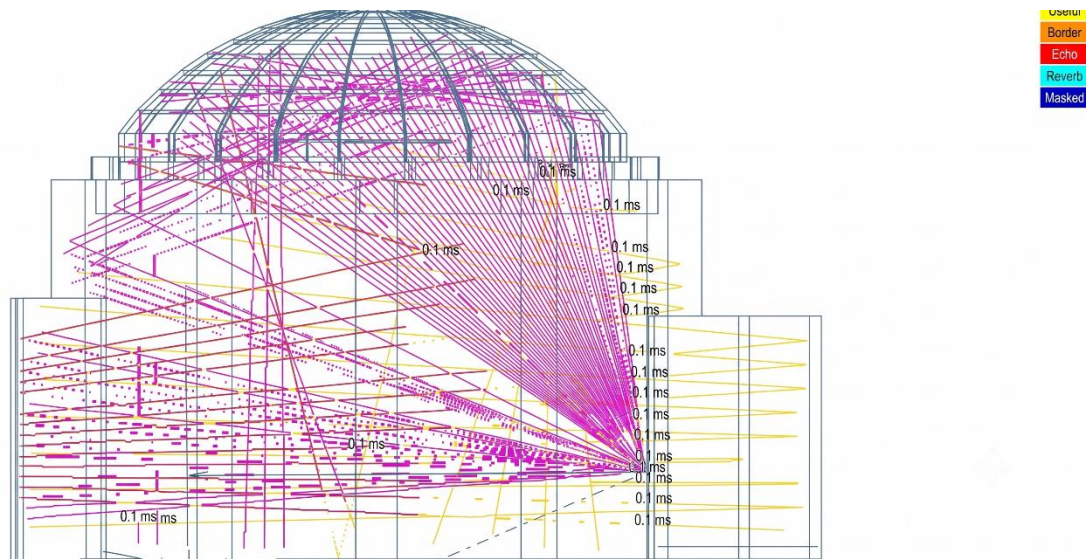


Figure 4. Time-delay analysis within the prayer hall.

#### 4.1.2 Altun Mosque (Large Rectangular Plan with Central Dome)

The Altun Mosque (29x33.2 m) is a massive rectangular structure with an 11 m-tall ceiling, reflecting a contemporary design that utilizes high, uncontrolled, uninterrupted volume. It is designed to accommodate 950 worshippers and has a 10,629 m<sup>3</sup> sanctuary, corresponding to a V/N ratio of 11.18 m<sup>3</sup> per person. In addition, due to the size of the uninterrupted volume, the RT<sub>60</sub> for the mosque does not meet the target for optimal performance (RT<sub>60</sub> = 1.11 s). The simulated RT<sub>60</sub> decay time at 500 Hz is 3.88 seconds, as shown in Table 3. Because of the great distance sound travels before striking reflective surfaces, the delayed-returning sound rays experience such a time delay that they arrive after the 50 ms critical threshold and mask direct vocal communication. The mosque also has inadequate low-frequency resonance control: the simulated RT<sub>60</sub> at 125 Hz is 9.53 s, and the bass ratio is 1.81, resulting in an acoustically "muddy" quality (low definition). Its distinct advantage is providing uniformly dispersed sound throughout, due to the rectangular floor plan, with no focal points of sound and a range of +1 dB to +4 dB across most of the floor area.

Table 3: statistical acoustic RT for Altun Mosque

Column 1 Frequency	TOTAL Absorption	SABINE RT (60)	NOR-ER RT (60)	MIL-SE RT (60)
63 Hz	28.098	8.88	10.17	10.4
125 Hz	27.691	8.36	9.53	5.77
250 Hz	27.199	4.16	4.43	3.56
500 Hz	26.593	3.66	3.88	3.27
1 kHz	25.826	3.6	3.8	3.29
2 kHz	24.812	3.19	3.34	2.99
4 kHz	23.399	3.26	3.41	3.1
8 kHz	21.234	2.85	2.96	2.77
16 kHz	17.31	2.78	2.85	2.73

### 4.1.3 Firdaws Mosque (Rectangular Plan with Hemispherical Dome)

The Firdaws Mosque exhibited the poorest acoustic performance among the investigated cases, highlighting the acoustic implications of excessive volumetric scaling. With an overall volume of 7,420 m<sup>3</sup> [4], the mosque has a main hall with rectangular-solid dimensions and a 20-meter dome forming a hemispheric geometry leading to the main floor. Although it can accommodate only 550 worshippers, it has the highest volume-per-person (V/N) ratio in this study, at 13.49 m<sup>3</sup>/person, approximately double the upper threshold established by international standards for building design, as shown in Fig. 5.

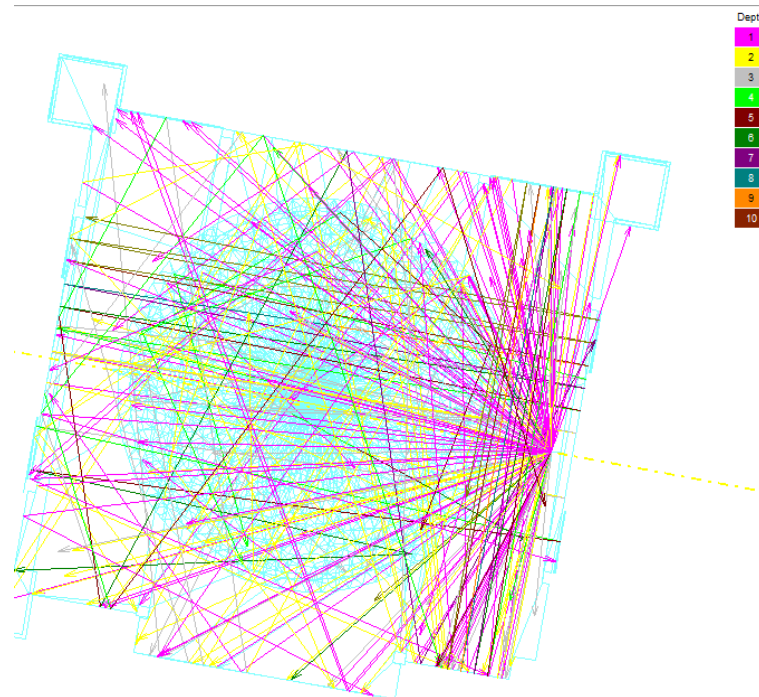


Figure 5: raytracing simulation of Firdaws Mosque (Author,2026)

The theoretical optimum  $RT_{60}$  for this space yields a time constant of 1.06 seconds; however, the simulation showed that under actual conditions, this time increased to 6.54 seconds at 500Hz (see Table 4).

Table 4: statistical acoustic RT for Firdaws Mosque

Frequency (FREQ)	Total Absorption	Sabine RT (60)	Norris-Eyring (NOR-ER) RT (60)	Millington-Sette (MIL-SE) RT (60)
63Hz	20.040	13.15	16.28	16.88
125Hz	19.749	12.53	15.41	7.42
250Hz	19.399	6.25	6.90	4.96
500Hz	18.966	5.94	6.54	4.96
1kHz	18.419	5.67	6.21	4.92
2kHz	17.696	4.65	4.99	4.23
4kHz	16.688	4.09	4.34	3.84
8kHz	15.144	2.54	2.63	2.47
16kHz	12.345	2.46	2.52	2.43

The theoretical optimum reverberation time for this mosque is 1.06 s. However, the simulation predicted an  $RT_{60}$  of approximately 6.54 s at 500 Hz as shown in (Table 4)

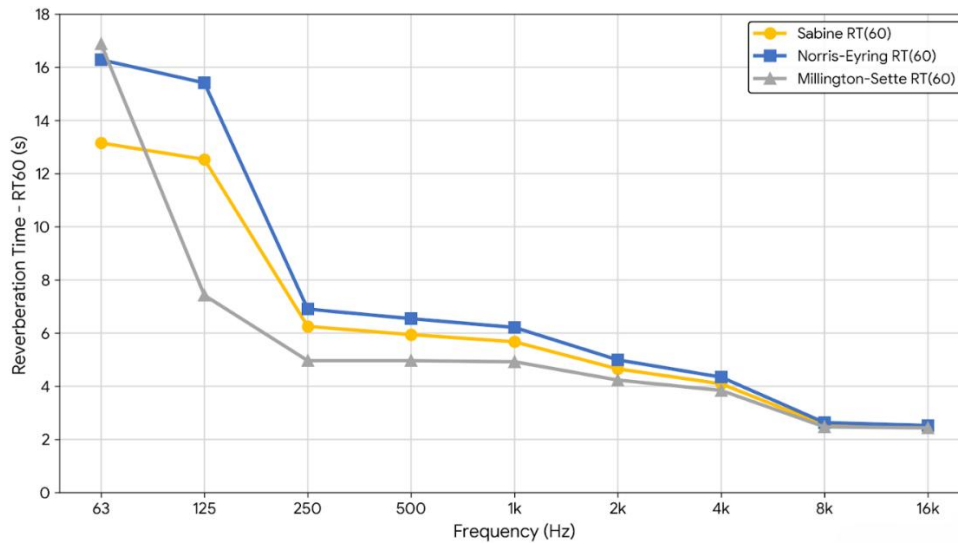


Figure 6. Comparison of  $RT_{60}$  calculation methods across Frequencies.

#### 4.1.4 Haji Dawood Mosque (Rectangular Plan with Multi-Cellular Domes)

In contrast to the acoustic limitations associated with large single-dome structures, the Haji Dawood Mosque has 14 small domes, a volume of 2,520 cubic meters, and a capacity for 350 worshippers. This gives it a V/N ratio of 7.20 m<sup>3</sup>/person, which is the optimal ratio for worshipper accommodation in such buildings. Although it is not within the strict  $RT_{60}$  target of 0.92 seconds for optimum acoustic performance ( $RT_{60}$  is approximately 2.47 seconds at 500 Hz, as per Table 5), it has spatial sound distributions that are many orders of magnitude superior to those of larger rectangular models.

Table 5: statistical acoustic RT for Haji Dawood Mosque

Frequency (FREQ)	Total Absorption (ABSPT)	Sabine RT (60)	Norris-Eyring (NOR-ER) RT (60)	Millington-Sette (MIL-SE) RT (60)
63Hz	10.192	5.66	6.10	6.60
125Hz	10.044	5.28	5.66	3.68
250Hz	9.865	2.66	2.80	2.28
500Hz	9.645	2.34	2.47	2.10
1kHz	9.367	2.27	2.39	2.08
2kHz	8.999	1.98	2.06	1.86
4kHz	8.487	1.93	2.00	1.84
8kHz	7.701	1.53	1.57	1.49
16kHz	6.278	1.49	1.53	1.48

This partial success has resulted from changing the roof from a single vault to fourteen smaller domed roofs, as depicted in Figure 7. Instead of a single vaulted roof, which would create a single return of sound energy to a given location, many different sound energy sources are created by fracturing sound energy into multiple areas across a base of many small domes. The "fracturing" of sound energy creates

an array of diffusers above the location, effectively preventing hot spots by preventing the high-frequency sound energy from returning to its origin, as shown in Figure 8.

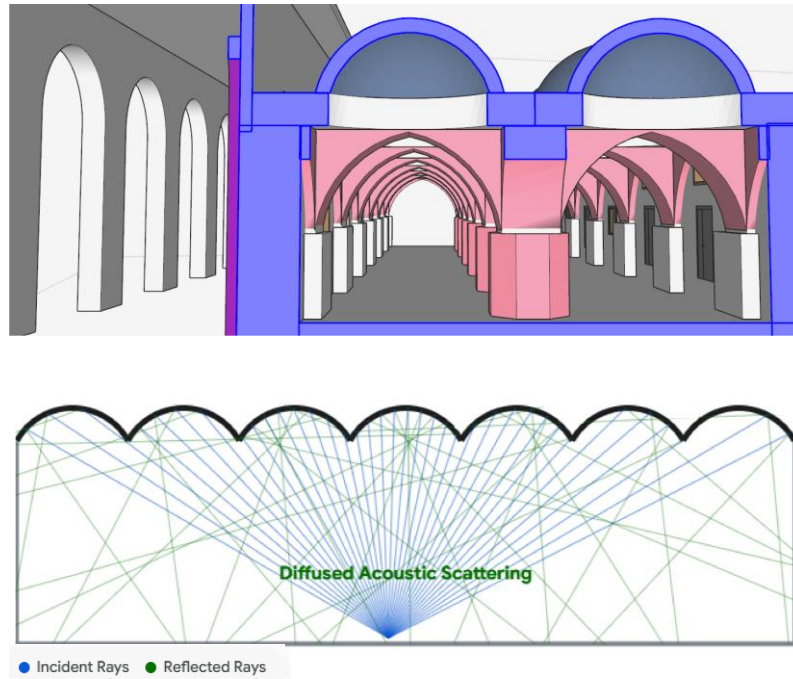


Figure 7: Shows the structure and fourteen domes of Haji Dawood Mosque and a simulated diffused acoustical scattering for fourteen domes of Haji Dawood Mosque (Author,2026)

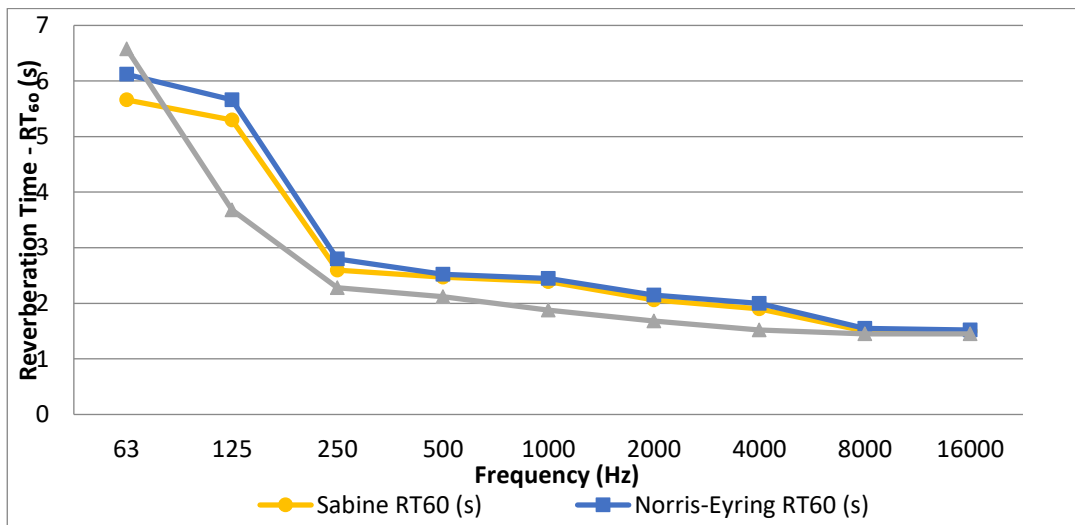


Figure 8: Comparison of RT<sub>60</sub> calculation methods across Frequencies for Haji Dawood Mosque (Author,2025)

#### 4.1.5 Koya Grand Mosque (Segmented Plan with Dense Structural Grid)

The Koya Grand Mosque holds significant historical value. Among the other examined mosques beside haji Dawood, the Koya Grand Mosque has the greatest restriction on unamplified acoustic performance. The sanctuary has a volume of 2,008 m<sup>3</sup> and is rated for 540 occupants, resulting in a density of 3.71 m<sup>3</sup>/person (the highest V/N density measured). Although the ideal mathematical RT for speech (0.89 s) was generated through computer simulation, the measured RT<sub>60</sub> was actually 1.29 s at 500 Hz (see Table 6). While this value is still greater than the ideal target, it represents a considerable improvement compared with the longest RT measures across other typologies (which exceeded 6.0 s).

The comparative control of acoustics is possible due to the building's load-bearing geometry. The internal grid formed by the masonry pillars in the sanctuary acts as an architectural acoustic regulator. It initiates reflection interactions early in the sequence, thereby encouraging a much more rapid attenuation of acoustic energy than a wide-open plan.

Table 6: statistical acoustic RT for Koya Grand Mosque

Frequency (Hz)	Total Absorption	Sabine RT (60)	NOR-ER RT (60)	MIL-SE RT (60)
<b>63Hz</b>	10.622	3.12	3.43	3.48
<b>125Hz</b>	10.468	2.95	3.22	2.24
<b>250Hz</b>	10.282	1.42	1.48	1.27
<b>500Hz</b>	10.052	1.24	1.29	1.15
<b>1kHz</b>	9.763	1.23	1.28	1.16
<b>2kHz</b>	9.379	1.10	1.13	1.05
<b>4kHz</b>	8.845	1.16	1.20	1.12
<b>8kHz</b>	8.027	1.08	1.11	1.05
<b>16kHz</b>	6.543	1.04	1.07	1.03

The dense internal grid of masonry pillars acts as an "acoustic attenuation mechanism." By forcing continuous acoustic scattering processes within the first 30 milliseconds of sound emission, the pillars rapidly strip kinetic energy from the room, as shown in Fig. 9.

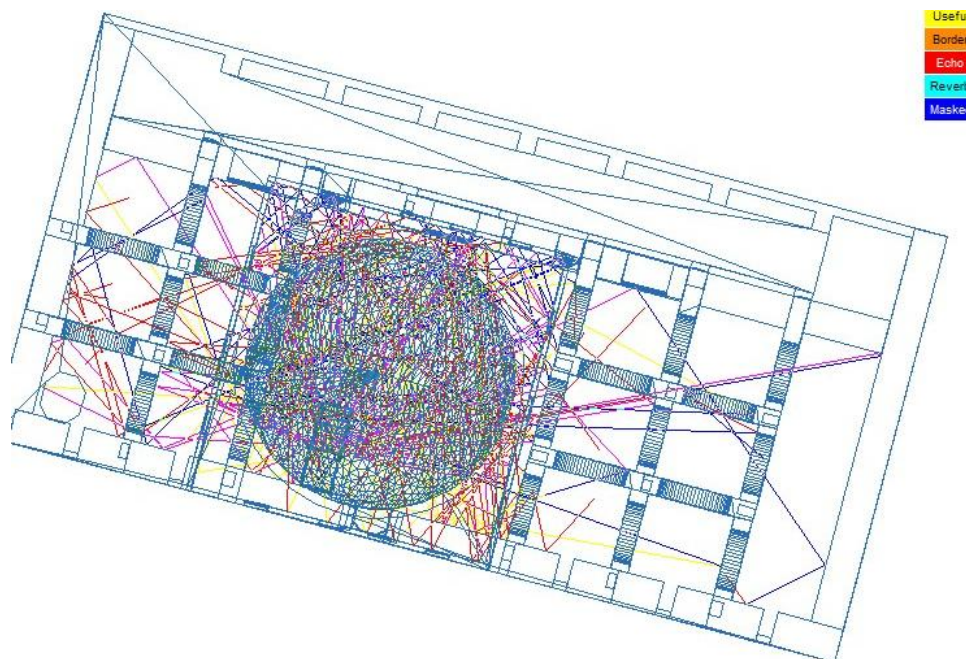


Figure 9: Comparison of RT<sub>60</sub> calculation methods across Frequencies (Author, 2026)

This structural segmentation achieves near-instantaneous attenuation across all frequencies yielding an exceptionally "dry" Bass Ratio and supporting improved speech intelligibility.

#### 4.2 Frequency-Dependent Reverberation Time ( $RT_{60}$ )

An analysis of the five major typologies demonstrated that, regardless of type, the number one contributing factor to the acoustic decay for each of the five mosque typologies is their size (or volume), or the fact that they were unbroken by architectural separations (or partitions) between the primary mass of that specific typology. The mosques that are characterized as high-volume unbroken by architectural partitions, such as the mosques of Firdaws and Altun, were found to have a mean reverberation time of 500 Hz considerably above the optimal range for speech intelligibility (i.e., for the Firdaws Mosque, the mean reverberation time was 5.94 seconds, and for the Altun Mosque, the mean reverberation time was 3.66 seconds, reference tables 4 and 3, respectively).

Thus, confirming that temporary accumulation (i.e., excessive reverberation) of sound over long periods of time occurs within a single, large volume of space. The Koya Grand Mosque exhibited a controlled, middle-of-the-road response time (i.e., 1.24 seconds at 500 Hz; reference table 6). However, it was still acoustically functional because it had minimal low-frequency buildup and a fairly uniform decay pattern over time, despite its overall reverberation time exceeding the theoretical optimum for speech (i.e., 0.89 seconds; reference table 7). This affirms what has previously been established: that actual deviations from optimum reverberation times for speech (i.e., measured in seconds) are not nearly as problematic/critical as the ability for those low-frequency sounds to build-up/accumulate in such a way (i.e., below 125 Hz) as to cause interference/masking of the speech.

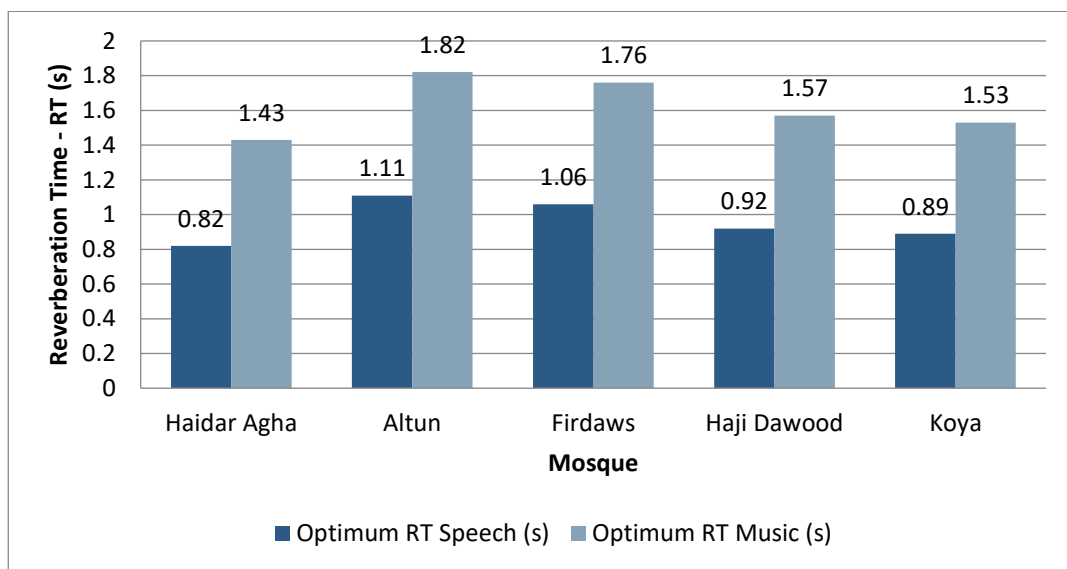


Figure 10: Optimum  $RT_{60}$  target thresholds for speech and music across the five mosque typologies (Author, 2026)

Additionally, the analysis of  $RT_{60}$  using standard octave bands (63 Hz to 16 kHz) reveals a universal flaw in high-volume typology buildings: extreme low-frequency resonance (see Figure 10). The immense, non-segmented volumetric structure of Firdaws Mosque produces an unacceptable decay time of 15.41 seconds at 125 Hz, in contrast with the standard finishing and occupancy materials used to successfully contain high-frequency energies (causing the curves to slope downward from 1kHz),

which appear translucent to these huge long-wavelength low-frequency sound waves, thus allowing them to reflect off hard surfaces in an uncontrolled manner.

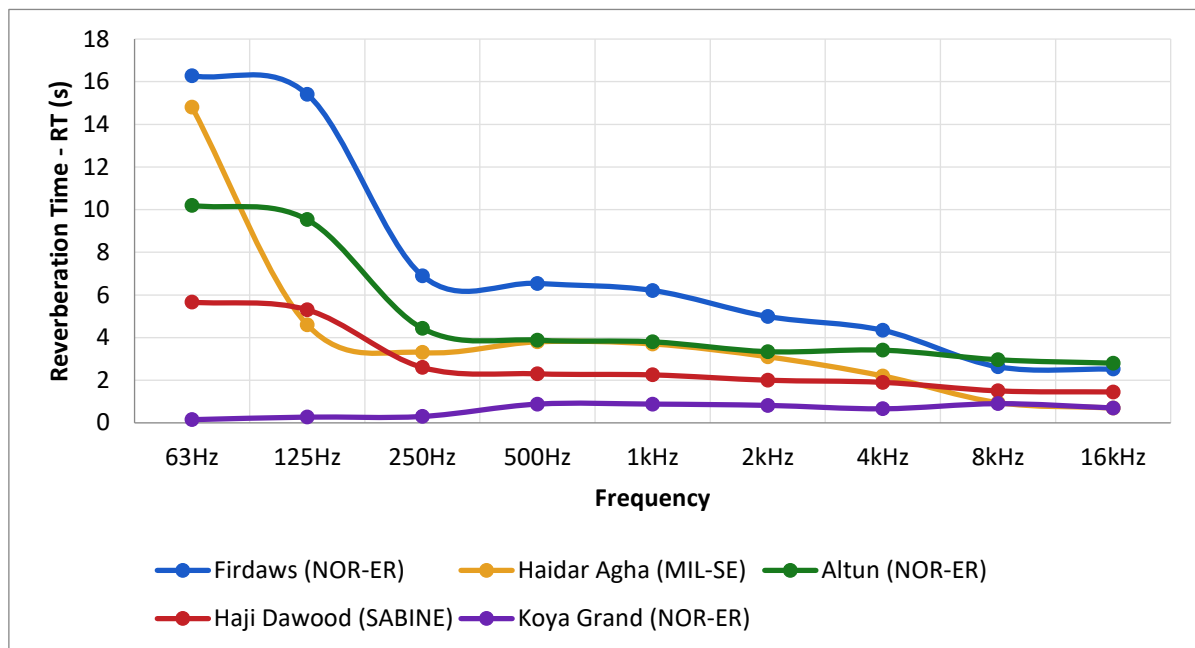


Figure 11: Frequency-dependent comparison of RT<sub>60</sub> values across the five mosque typologies (Author,2026)

In contrast, the Koya Grand Mosque, historically, achieves the highest level of natural acoustic performance, meeting its standard speech time of 0.89 s (Refer to Table 7). The nearly flat trajectory of the spectral curve for Koya (see Figure 11) indicates excellent decay control across the full frequency spectrum. The interior of Koya features a dense grid of masonry pillars that serve as an acoustic control element. The division of the walls creates a volumetric mass that produces fast, repeated sound-wave interactions that cancel out the low-frequency spikes and produce clarion-quality speech only through the load-bearing structure.

Table 7: Comparison of Optimum RT for Speech vs. Music (500 Hz)

Mosque Name	Geometry Type	Optimum RT Speech (500 Hz)	Optimum RT Music (500 Hz)
<b>Haidar Agha</b>	Circular + Quarter Dome	<b>0.82 s</b>	1.43 s
<b>Altun</b>	Rectangular + Dome	<b>1.11 s</b>	1.82 s
<b>Firdaws</b>	Rectangular + Dome	1.06 s	1.76 s
<b>Haji Dawood</b>	Rectangular	0.92 s	1.57 s
<b>Koya</b>	Rectangular + Dome	0.89 s	1.53 s

### 4.3 Spatial Sound Distribution and Ray-Tracing

The spatial distribution of sound varies greatly with geometry rather than just volume, as shown by a ray-tracing study. In domed buildings (Haidar Agha, Altun, and Firdaws), reflected energy will produce concentrated focal zones based on the surface curvature and scale, or delayed diffuse fields based on the same factors. The simulations demonstrate how reflection clustering occurs and that many reflections arrive after 50ms (the intelligibility threshold) in the examples shown in Figures 3 and 6.

Conversely, sound at Koya Grand Mosque coheres based on early scatterings produced by its dense column grid. Figure 9 illustrates how sound energy is fragmented into numerous micro-reflection paths, resulting in fewer localized sound concentration zones, thereby improving spatial uniformity. Importantly, the temporal and spatial redistribution of reverberation does not eliminate the sound's reverberation; rather, it causes longer mid-frequency decay.

## 5. Discussion

The simulation results demonstrate that spatial morphology plays a significant role in shaping the acoustic performance of mosque prayer halls. Analysis of frequency-dependent reverberation behavior and sound distribution patterns (Figure 11) reveals substantial variation among the investigated typologies. Mosques characterized by large continuous interior volumes and dominant central domes exhibited prolonged reverberation times and greater low-frequency sound accumulation, whereas configurations incorporating distributed dome systems or structural articulation demonstrated more controlled acoustic behavior. Within the investigated cases, spatial morphology emerged as a dominant factor influencing reverberation control and speech-related acoustic performance under similar occupancy and material conditions.

### 5.1 Impact of Architectural Geometry

In conclusion, The results indicate that architectural geometry is more influential than volumetric scaling alone in determining acoustic behavior and cannot be fully predicted using volume-based methods alone. For example, the Haidar Agha Mosque shows a significant discrepancy between the theoretical calculations using  $RT_{60}$  values and the results from simulations. Theoretically,  $RT_{60}$  predictions are based on Geometrical acoustics because the building has a particular geometric arrangement: circular geometry and a quarter dome. The result of these two geometric characteristics is that sound tends to reflect inward toward the center of the building rather than uniformly across it (as seen in Figures 3 and 4). Likewise, while the Koya Grand Mosque has an  $RT_{60}$  value (theoretical optimum of 0.89 seconds compared to the actual  $RT_{60}$  value of 1.24-1.29 seconds) that exceeds the expected  $RT_{60}$  value, the performance of this building relative to the speech intelligibility test is acceptable because of structural segmentation effects (as shown in Figure 9). This further demonstrates that  $RT_{60}$  is insufficient on its own to evaluate speech intelligibility in complex architectural spaces.

### 5.2 Volumetric Scaling and Low-Frequency Resonance

The new findings support the idea that continuous volume scaling is more strongly correlated with low-frequency amplification than with the material it is made of. Firdaws and Altun (the large, unsegmented mosques) both have very prolonged low-frequency decay times (Firdaws: 125 Hz = 15.41 s) (see Table 4). As a result, low-frequency decay produces masking, which affects the clarity of the vowels we hear and how easily we can understand a speaker. The Koya Grand Mosque, on the other hand, has a significantly shorter duration of low frequencies (125 Hz = 2.95-3.22) (see table 6). This demonstrates that if you can build a structure using segments, modal buildup will be effectively controlled before the modal reaches its full duration.

### 5.3 Dome-Induced Sound Focusing

Single massive domes (Haidar Agha) cause severe acoustic distortion by concentrating sound energy into tight spatial nodes higher than the room average. Conversely, replacing a single dome with a multi-cellular configuration (as in the 14-dome Haji Dawood Mosque) functions as an overhead diffuser array. These fractures return sound waves into a highly scattered, uniform field, entirely preventing localized sound concentration zones despite a slightly elevated overall  $RT_{60}$  (2.47 s).

### 5.4 Structural Segmentation for Sound Attenuation

The study demonstrates that architectural segmentation demonstrates superior relative performance to open floor plans in managing reverberation. While unsegmented halls allow sound waves to travel 30

to 40 meters unchecked, degrading speech clarity, the Koya Grand Mosque's dense pillars act as an " sound-scattering structural system. These structures force continuous reflection interactions that rapidly dissipate acoustic energy, significantly reducing late reverberation and supporting optimal speech intelligibility.

### 5.5 Computational Limitations and Uncertainty Quantification

While computational geometric acoustics provides robust comparative insights, ray-tracing algorithms struggle with long-wavelength phenomena; thus, the severe low-frequency resonances recorded (e.g., at 125 Hz) may actually under-represent the true severity of modal standing waves. Furthermore, relying on standardized material absorption databases introduces a  $\pm 5\%$  to  $\pm 10\%$  margin of error compared to real-world aging materials. Finally, modeling human occupancy as a static plane fails to capture the dynamic acoustic shifts that occur as a congregation transitions between sitting during sermons and active movement during prayer.

### 5.6 Architectural Implications and Future Research

Unsegmented monumental volumes severely degrade acoustic functionality. Architects should prioritize segmented rectangular halls (1:2 to 1:4 aspect ratios). If massive domes are required, absorptive liners must be used to prevent acoustic focusing, and dedicated bass traps must be used to mitigate extreme low-frequency (125 Hz) resonance. Future research should combine geometric ray tracing with Finite Element Method (FEM) simulations and validate these computational predictions through real-world in situ post-occupancy measurements.

## 6. Conclusion

This study investigated the influence of spatial morphology on the acoustic performance of mosque prayer halls through a comparative simulation-based analysis of five contemporary mosque typologies in the Kurdistan Region of Iraq. The findings demonstrate that architectural geometry is a primary determinant of acoustic performance when occupancy conditions and material properties are held constant. The results showed that large, continuous interior volumes with dominant central domes consistently produced prolonged reverberation times, excessive low-frequency sound accumulation, and localized sound-focusing effects, thereby reducing speech intelligibility. In contrast, prayer halls incorporating spatial segmentation through distributed dome systems or structural articulation exhibited more balanced sound distribution, reduced low-frequency resonance, and acoustic conditions that more closely approached recommended reverberation targets for speech.

The results further demonstrate that reverberation time alone is insufficient to characterize acoustic quality in complex worship spaces. Ray-tracing analysis revealed that the spatial distribution of reflected sound energy and the degree of architectural segmentation substantially influence sound propagation, reflection behavior, and speech clarity. Among the investigated typologies, segmented spatial configurations achieved the most effective reverberation control by promoting early sound scattering, reducing the formation of strong late reflections, and limiting excessive low-frequency sound buildup, even when reverberation times remained slightly above theoretical optimum values. These findings confirm that architectural geometry should be considered an active acoustic design strategy rather than merely a spatial or aesthetic characteristic.

From an architectural perspective, the findings emphasize the importance of integrating acoustic considerations during the earliest stages of mosque design. Spatial organization, volumetric composition, dome configuration, and structural articulation should be treated as fundamental design parameters for achieving acoustically effective worship spaces rather than relying primarily on post-construction acoustic treatments. Although this study is based on computational simulations, it provides a robust framework for geometry-driven acoustic design.

Future research should validate these findings through in-situ acoustic measurements across a broader range of mosque typologies and incorporate additional acoustic performance indicators to further strengthen evidence-based design guidelines for contemporary religious buildings.

**Conflict of Interest:** There is no conflict of interest.

#### **AI tool Declaration:**

The authors declare that any AI tools used in the preparation of this manuscript were limited to language and readability improvement only and were not used to generate scientific content, data, analyses, or conclusions, with full responsibility retained by the author.

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