Dynamic In-Cabin Acoustic Evaluation: Characterizing Road and Speed Contributions to Interior Vehicle Noise Levels for Passenger Comfort

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ABSTRACT

Interior acoustic comfort plays a decisive role in driver fatigue mitigation, speech intelligibility, and overall customer perception of build quality in modern passenger automobiles. While stationary dynamometer evaluations provide controlled acoustic baselines, they routinely underestimate the combined vibro-acoustic excitation encountered in daily commuter environments. This study evaluates dynamic in-cabin Sound Pressure Levels (SPL) across three contrasting driving environments in Peninsular Malaysia: urban collector corridors, undulating rural secondary roads, and high-speed multi-lane expressways. Field measurements were logged using a high precision digital sound level meter across synchronized temporal windows (morning peak, evening peak, and nighttime off-peak) using two mass-market compact vehicles, a 1.5L B-segment hatchback and a 1.0L A-segment entry commuter benchmarked against an elevated C-segment crossover. Across all environmental domains, operating velocity and tire-pavement interaction emerged as the primary acoustic drivers, overshadowing static ambient congestion effects. Cabin sound levels escalated from 75.1 to 82.4 dB(A) at low-speed urban cruising (40–60 km/h) to sustained maximum levels of 99.3–106.7 dB(A) during expressway transit (80–100 km/h). The lighter 1.0L platform exhibited consistently higher cabin decibel penalties (2.5 to 7.4 dB(A) higher than the 1.5L platform), particularly under pavement surface irregularities and wet conditions. These findings underscore the imperative for targeted localized floor pan damping and improved wheel-arch acoustic barriers in entry-level vehicle manufacturing.

Keywords: In-cabin acoustic comfort, automotive NVH, on-road sound measurement, tire-pavement interaction, vehicle interior noise, structure-borne vibration

INTRODUCTION

Modern passenger vehicle buyers increasingly perceive interior quietness and the attenuation of acoustic disturbance as direct indicators of structural build quality and engineering refinement (Birlik & Sezgin, 2003). Prolonged exposure to elevated sound levels inside an automobile cabin induces cognitive fatigue, diminishes vocal communication intelligibility, accelerates driver stress, and degrades psychoacoustic ride quality (Chiesa, 1964). Consequently, the discipline of Noise, Vibration, and Harshness (NVH) has shifted from an aftermarket troubleshooting concern into an indispensable parameter in chassis development, BIW (body-in-white) stiffening, and passenger compartment architecture (Wang, 2010).

Acoustic energy penetrating the passenger cabin originates from diverse and coupled physical pathways, traditionally classified into airborne and structure-borne mechanisms (Putra et al., 2012). Structure-borne interior noise dominates lower frequency ranges (typically below 500 Hz) and is primarily generated by dynamic powertrain combustion pulses, transmission gear meshing, and chassis suspension vibration induced by road surface roughness and transmitted directly into the floor pans and firewall (Sjoerdsma, 2005). Conversely, airborne sound propagates externally through surrounding fluids and enters through localized

door seals, glass apertures, and air intake systems, driven by aerodynamic vortex separation at higher velocities (>90 km/h) and direct tyre-tread air compression against asphalt textures (Arslan, 2010; Harrison, 2004).

In rapidly motorizing Southeast Asian countries, evaluating real-world interior acoustics presents unique physical complexities. Urban agglomerations in Malaysia consistently record some of the highest regional traffic congestion indices, necessitating frequent stop-and-go cycles, elevated ambient exterior noise from high density motorcycle traffic, and varied road paving standards ranging from coarse aggregate chip seals to smooth asphalt concrete. Although finite-sized semi-anechoic test chambers with chassis dynamometers enable reproducible pass-by noise quantification (Arslan, 2010), they fail to encapsulate dynamic structural deflections, aerodynamic crosswinds, and localized pavement excitation occurring on actual public roads. Surface damping treatments and constrained layer viscoelastic damping pads applied to vulnerable structural points (e.g., wheel wells, floor pans, and door panels) must be calibrated against real-world road input (Comesana & Tatlow, 2018). To bridge this empirical gap, this study executes a systematic, in-situ dynamic interior acoustic investigation comparing two high-volume passenger vehicles across varying road categories and commuter timeframes.

METHODOLOGY

The research methodology was executed in sequential phases encompassing vehicle platform selection, instrumentation calibration, route categorization, and parameterized on-road trials across synchronized timeframes.

Experimental vehicle selection

To characterize the acoustic behavior representative of mainstream regional commuters, two prominent Malaysian domestic passenger cars were selected: a 1.5L naturally aspirated B-segment five-door hatchback (Vehicle A) and a 1.0L three-cylinder entry-level A-segment compact (Vehicle B) are shown in Table 1. Prior to experimental testing, both vehicles underwent comprehensive mechanical inspections to ensure powertrain mounting integrity, standard tyre inflation pressures, and the absence of abnormal wheel-bearing or exhaust rattles. A turbocharged 1.5L C-segment sport utility vehicle (Vehicle C) was utilized during preliminary boundary trials to calibrate instrumentation logging rates on long-distance expressway stretches.

Table 1. Technical specifications and experimental control parameters of test vehicles

VEHICLE MODEL PARAMETER	VEHICLE A	VEHICLE B	VEHICLE C
Vehicle Segment / Class	B-segment Subcompact Hatchback	A-segment Mini Urban Hatchback	C-segment Compact SUV
Engine Capacity	1496 cc, Inline-4 DOHC	988 cc, Inline-3 DOHC	1498 cc, Turbocharged Inline-4
Horsepower	102 hp @ 6,000 rpm	67 hp @ 6,000 rpm	190 hp @ 5,600 rpm
Maximum Torque	136 Nm @ 4,200 rpm	91 Nm @ 4,400 rpm	243 Nm @ 2,000 rpm
Passenger Occupancy Occupant Loading Control	4 Passengers (controlled)	4 Passengers (controlled)	4 Passengers (controlled)
Interior Cabin Acoustic Setup	Blower speed 1	Blower speed 1	Blower speed 1
	(Off-audio, closed)	(Off-audio, closed)	(Off-audio, closed)

Instrumentation and Sensor Positioning

Sound pressure level (SPL) data acquisition was conducted using a calibrated TASI TA653B digital precision sound level meter equipped with a 6 mm prepolarized capacitive microphone sensor. The device possesses an operational dynamic measurement range of 30.0 dB to 130.0 dB(A), an acoustic frequency response spanning 31.5 Hz to 8.5 kHz, an instrument accuracy of ±1.5 dB, and an internal digital resolution of 0.1 dB. Data sampling occurred continuously with 2-second internal hardware logging, while discrete mean sound pressure levels were compiled at standardized 5-minute checkpoints across each 30-minute test cycle.

To capture both front-cabin operator exposure and rear-passenger acoustic field propagation, the microphone unit was rigidly fixture-mounted in two designated interior positions: (i) the primary dashboard center console aligned with passenger ear level, and (ii) the rear passenger compartment midpoint between the B-pillar and C-pillar acoustic cavities. All trials maintained sealed window apertures, deactivated audio infotainment systems, and static low-speed ventilation to avoid localized aerodynamic hiss over the microphone diaphragm.

Route Selection and Operational Speed Regimes

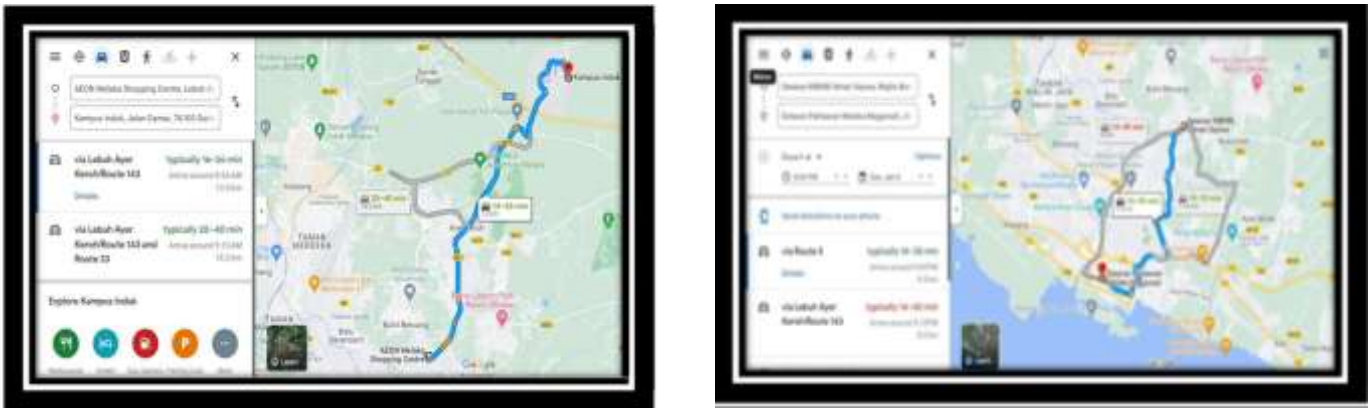
Experimental routes were classified into three distinct geographic and functional road typologies across the state of Melaka, Malaysia, intentionally selected to introduce varying road pavement textures, topographic elevations, and external traffic densities:

Category 1: Urban / City Corridors (Figure 1). Route 1 spanned from AEON Melaka Ayer Keroh to the UTeM Main Campus via Federal Route 143 (13.3 km). Route 2 covered the historical commercial center between Dataran MBMB Ayer Keroh and Dataran Pahlawan Megamall (9.5 km). Cruising velocities were maintained between 70 km/h and 90 km/h where permissible, interspersed with characteristic urban deceleration cycles.

Category 2: Rural Secondary Arteries (Figure 2). Route 1 traversed Taman Tun Kudu, Bukit Katil to Jasin town via State Route M144 (20.2 km). Route 2 connected Durian Tunggal to Selandar via Route M19 (24.1 km). Operating speeds were maintained within a controlled band of 40 km/h to 60 km/h over undulating asphalt surfaces bounded by open vegetation.

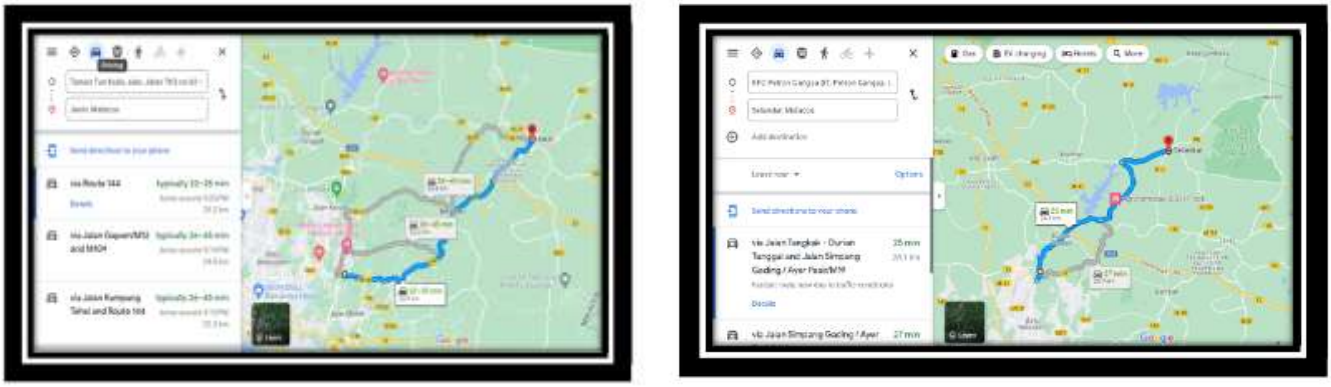
Category 3: Inter-Urban Expressways (Figure 3). Route 1 spanned the North-South Expressway (PLUS - E2) from Ayer Keroh Toll Plaza to Simpang Ampat Toll Plaza (23.4 km). Route 2 covered Federal Route 33 (Lebuh SPA) from Cheng interchange to UTeM Technology Campus (7.4 km). Test vehicles operated at steady-state cruising velocities between 80 km/h and 100 km/h.

To isolate temporal traffic variations, every test route was sampled across three specific diurnal timeframes: Morning Peak (07:30–09:00), Evening Peak (16:30–18:30), and Night Off-Peak (21:00–23:00).



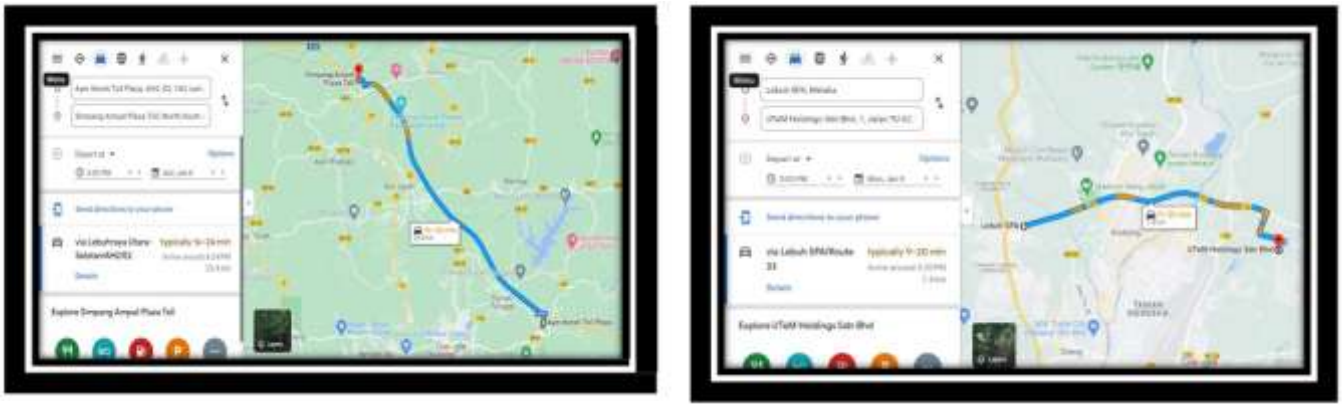
(a) (b)

Figure 1. City routes: (a) a 13.9 km drive from AEON Ayer Keroh to the UTeM Main Campus, and (b) a 9.5 km stretch connecting Dataran MBMB Ayer Keroh to Dataran Pahlawan Mall



(a) (b)

Figure 2. Rural routes: (a) a 20.2 km drive from Taman Tun Kudu in Bukit Katil to Jasin, and (b) a 24.1 km stretch connecting Petron Gangsa in Durian Tunggal to Selandar.



(a) (b)

Figure 3. Highway routes: (a) a 23.4 km stretch along the PLUS Highway from Ayer Keroh Toll Plaza to Simpang Ampat Toll Plaza, and (b) a 7.4 km drive along Lebuh SPA from Cheng to the UTeM Technology Campus

RESULTS AND DISCUSSION

Urban In-Cabin Sound Dynamics (Category 1)

Data logged across urban routes shown in Table 2 indicated moderate overall interior noise levels punctuated by external ambient traffic fluctuations. In the Ayer Keroh urban corridor during the morning peak hour, Vehicle A's SPL increased from 75.6 dB(A) at 5 minutes to 87.6 dB(A) at 30 minutes. Vehicle B demonstrated higher initial and terminal SPLs, recording 79.9 dB(A) and 94.5 dB(A), respectively. During the evening peak hour, SPLs followed an upward trajectory for both platforms, with Vehicle A stabilizing at 91.2 dB(A) and Vehicle B reaching 94.1 dB(A) as stop-and-go congestion surrounding arterial intersections concentrated heavy commercial vehicles and motorcycles alongside the vehicle cabin flanks.

A similar pattern emerged along the Malacca City Centre route (Dataran MBMB to Dataran Pahlawan). In morning trials, Vehicle A recorded sound pressure levels progressing from 75.6 dB(A) to 88.5 dB(A), while Vehicle B exhibited greater sensitivity to pavement transitions, peaking at 94.7 dB(A). Night time measurements across the urban center exhibited the lowest baseline values (Vehicle A starting at 75.5 dB(A); Vehicle B at 78.6 dB(A)), reflecting reduced ambient commuter density and smoother steady-state velocity profiles free from abrupt braking cycles.

Table 2: Discrete in-cabin SPL measurements over 30 minutes in Category 1 (Urban Route)

Vehicle Platform	Timeframe	5 min (dB)	10 min (dB)	15 min (dB)	20 min (dB)	25 min (dB)	30 min (dB)	Mean ± SD
Vehicle A (1.5L)	Morning Peak	75.6	83.3	82.4	84.5	86.7	87.6	83.35 ± 4.25
Vehicle B (1.0L)	Morning Peak	79.9	86.7	92.3	83.8	89.9	94.5	87.85 ± 5.48
Vehicle A (1.5L)	Evening Peak	77.3	83.5	78.4	88.6	90.4	91.2	84.90 ± 5.92
Vehicle B (1.0L)	Evening Peak	75.4	84.2	83.4	84.3	93.2	94.1	85.77 ± 6.95
Vehicle A (1.5L)	Night Off-Peak	75.4	78.9	79.9	80.4	84.4	90.7	81.62 ± 5.34
Vehicle B (1.0L)	Night Off-Peak	76.7	77.8	83.7	85.4	90.6	94.1	84.72 ± 6.84

Rural Secondary Arteries Noise Profiles (Category 2)

Operating across rural routes (Jasin and Durian Tunggal–Selandar) as shown in Table 3 below placed both vehicles in lower-speed operating bands (40–60 km/h) but exposed them to uneven road surfaces, transverse asphalt cracks, and localized chip-seal paving. On the Bukit Katil–Jasin rural corridor, a remarkably uniform, linear increase of interior noise occurred. Vehicle A increased steadily from 79.4 dB(A) to 90.3 dB(A) in morning runs, while Vehicle B registered a parallel rise from 81.3 dB(A) up to 94.5 dB(A). During this specific morning trial, localized rainfall induced tire-splash airborne noise, amplifying the acoustic differential between the two vehicle shells.

On the Durian Tunggal to Selandar route, evening tests produced the highest rural decibel levels. Vehicle A's sound level increased from 78.6 dB(A) to 92.9 dB(A), whereas Vehicle B's sound level increased from 79.9 dB(A) to 95.3 dB(A). The steady progression observed across all rural trials demonstrates that even in the absence of dense external traffic queues, structural vibration transmitted via uninsulated suspension mounting hard points directly excites the passenger compartment cavity.

Table 3: Discrete in-cabin SPL measurements over 30 minutes in Category 2 (Rural Route)

Vehicle Platform	Timeframe	5 min (dB)	10 min (dB)	15 min (dB)	20 min (dB)	25 min (dB)	30 min (dB)	Mean ± SD
Vehicle A (1.5L)	Morning	79.4	81.3	83.2	84.6	87.3	90.3	84.35 ± 4.04
Vehicle B (1.0L)	Morning	81.3	84.5	85.3	87.2	88.9	94.5	86.95 ± 4.45
Vehicle A (1.5L)	Evening	75.7	78.3	82.4	85.3	87.3	89.5	83.08 ± 5.34
Vehicle B (1.0L)	Evening	78.8	82.3	85.6	87.8	90.3	92.5	86.22 ± 5.09
Vehicle A (1.5L)	Night	75.1	80.5	80.3	83.2	86.3	88.5	82.32 ± 4.79
Vehicle B (1.0L)	Night	81.3	84.7	83.4	87.8	89.1	91.2	86.25 ± 3.70

Expressway and Highway Noise Accumulation (Category 3)

The inter-urban expressway sector (PLUS E2 Highway from Ayer Keroh Toll to Simpang Ampat) produced the most severe acoustic exposure recorded in this research. Operation at steady-state velocities of 80 km/h to 100 km/h elevated both aerodynamic wind shear across the A-pillars and continuous tire carcass vibration. As detailed in Table 4, morning peak trials resulted in Vehicle A's sound level climbing from 82.3 dB(A) up to 99.3 dB(A). Vehicle B breached the 100 dB threshold by minute 25 (100.9 dB(A)) and the interior sound level peaked at 106.7 dB(A) at minute 30.

On the Lebuh SPA dual-carriageway corridor, consistent increments occurred across morning, evening, and night sessions. Vehicle A exhibited a closely controlled range, rising from 77.3 dB(A) to 85.7 dB(A) in the morning and

77.4 dB(A) to 90.6 dB(A) in the evening. In comparison, Vehicle B consistently tracked 2.5 to 7.2 dB(A) higher, confirming that structural damping deficiencies in smaller unibody structures exacerbate noise buildup under continuous high-speed cruising.

Across all 18 evaluated drive-cycles, Vehicle B (1.0L A-segment) systematically generated higher interior noise levels than Vehicle A (1.5L B-segment). This persistent gap stems from structural differences: thinner gauge floor panels, reduced acoustic mastic application, absence of heavy wheel-arch liners, and a 3-cylinder engine operating at higher rotational speeds (~3,200 rpm vs ~2,400 rpm at 90 km/h) to maintain equivalent momentum.

Table 4: Discrete in-cabin SPL measurements over 30 minutes in Category 3 (PLUS Highway Route)

Vehicle Platform	Timeframe	5 min (dB)	10 min (dB)	15 min (dB)	20 min (dB)	25 min (dB)	30 min (dB)	Mean ± SD
Vehicle A (1.5L)	Morning Peak	82.3	92.6	93.1	96.4	98.4	99.3	93.68 ± 6.16
Vehicle B (1.0L)	Morning Peak	85.7	90.4	91.0	97.5	100.9	106.7	95.37 ± 7.91
Vehicle A (1.5L)	Evening Peak	85.4	88.8	90.5	91.7	93.9	95.6	90.98 ± 3.61
Vehicle B (1.0L)	Evening Peak	86.7	89.5	90.9	93.6	96.7	98.9	92.72 ± 4.54
Vehicle A (1.5L)	Night Off-Peak	86.3	87.9	89.1	90.5	92.7	96.8	90.55 ± 3.73
Vehicle B (1.0L)	Night Off-Peak	88.3	90.1	94.5	96.7	97.1	99.5	94.37 ± 4.31

Preliminary Benchmark Comparison (Vehicle C)

Preliminary long-distance highway validation conducted using Vehicle C along a 62.2 km expressway stretch (Ayer Keroh to Pagoh R&R) provided a critical benchmark. Under high-speed cruising, Vehicle C exhibited an overall mean interior SPL of 90.2 dB(A), with a logged minimum of 61.3 dB(A) during decelerations and transient peaks reaching 127.5 dB(A) during heavy aggregate rumble-strip crossings. This baseline demonstrates that even larger C-segment vehicles with advanced sub frame isolation experience intense acoustic excitation at sustained highway velocities, though their passive attenuation of airborne wind hiss remains visibly superior to subcompact platforms.

CONCLUSION

This empirical research successfully evaluated interior vehicle acoustic comfort across three distinct operational road categories in Malaysia using on-road dynamic measurement protocols. The principal conclusions derived from this work are:

1. **Velocity Outweighs Congestion Density:** While urban traffic congestion introduces transient acoustic peaks from surrounding vehicular horns and exhausts, vehicle operational speed constitutes the primary determinant of sustained cabin noise. Expressway travel (80–100 km/h) generated mean cabin SPLs of 93.6 dB(A) in Vehicle A and 95.3 dB(A) in Vehicle B, compared to 81.6–84.9 dB(A) during urban transit.

2. **Structural Mass and Damping Discrepancy:** The smaller 1.0L A-segment platform exhibited inferior acoustic isolation compared to the 1.5L B-segment across all conditions, recording decibel penalties of up to 7.4 dB(A) under identical highway profiles. This disparity is governed by lighter body panel gauges, reduced structural damping, and engine powertrain gear ratios requiring higher engine speeds.

3. **Environmental and Meteorological Sensitivity:** Pavement surface coarseness and wet weather conditions significantly amplify tire-pavement airborne roar, introducing up to 5 dB(A) of additional in-cabin noise that directly bypasses standard unlined wheel wells.

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