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Review

Manufacturing and Assembly Variability in Electric Drivetrains: Impacts on NVH Performance—A Review

Krisztian Horvath

Department of Vehicle Development, Audi Hungaria Faculty of Engineering, Széchenyi István University, Egyetem tér 1, 9026 Győr, Hungary; horvath.krisztian@ga.sze.com

Abstract

Considerable progress has been made in predicting nominal NVH behavior in electric drivetrains, but the acoustic scatter observed across manufactured units remains insufficiently understood. In practice, nominally identical drive units may still exhibit noticeably different tonal behavior because small deviations in gears, shafts, bearings, fits, centering features, or assembly phase modify the excitation, transfer, and radiation mechanisms of the system. This review examines how manufacturing and assembly variability influences NVH performance in electric drive units and e-axles, with particular focus on the rotor–shaft–gear–bearing–housing system. Unlike broader EV NVH reviews, the present work focuses specifically on variability-induced acoustic scatter and its propagation along the drivetrain NVH generation and transmission path. To support transparency and consistency, the literature search and selection process followed a structured, PRISMA-inspired approach across Scopus, Web of Science, Google Scholar, and SAE Mobilus for the 2015–2026 period. From 387 identified records, 50 studies were retained after duplicate removal, screening, and full-text assessment. The selected literature was synthesized into eight thematic categories: imbalance; run-out and eccentricity; bearing clearance and preload; spline and pilot centering; thermal effects; phase indexing; transmission error and sidebands; and end-of-line NVH diagnostics. The reviewed literature shows that manufacturing- and assembly-induced deviations can significantly alter transmission error, sideband structure, shaft-order content, and final tonal response, even when individual components remain within nominal tolerance limits. Beyond synthesizing the evidence base, the review organizes existing modeling and diagnostic practices into a structured framework for variability-aware NVH assessment, based on explicit deviation parameterization, hierarchical model fidelity, intermediate excitation metrics, thermal-state awareness, and closer integration with production and measurement data. Overall, the findings support a shift from nominal NVH assessment toward robustness-oriented, production-representative interpretation and future prediction of acoustic scatter in electric drivetrains.

Keywords: electric drivetrain; e-axle; NVH; manufacturing variability; assembly variability; transmission error; run-out; bearing preload; spline coupling; sidebands; end-of-line testing; robust simulation

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1. Introduction

Considerable progress has been made in modeling nominal NVH behavior in electric drivetrains, yet the variability observed across manufactured units remains insufficiently understood. In practice, nominally identical electric drive units may exhibit noticeable differences in tonal response. This is caused by small deviations in gears, shafts, bearings, centering features, fits, or assembly phase, which modify excitation mechanisms and their transfer to the housing and surrounding acoustic field [1]. This highlights the need to treat such deviations as system-level contributors to NVH behavior rather than purely as manufacturing quality issues.

This issue is particularly important in electric drive units and e-axles, where tonal phenomena are highly perceptible and acceptance limits are increasingly strict [1]. Unlike conventional powertrains, EV drive units often use simple single- or two-stage transmissions operating at high speed and torque, so even minor geometric deviations can become acoustically relevant. The absence of masking combustion noise further increases the perceptibility of gear-, shaft-, and bearing-related tonal features [1,2]. As a result, manufacturing and assembly variability—such as imbalance, misalignment, run-out, or clearance variation—can significantly influence the final NVH behavior of the assembled unit [3]. Recent studies also show that even micrometer-scale deviations, including tooth-spacing errors or rotor eccentricity, may generate ghost orders or sideband tones that would have been less noticeable in conventional drivetrains [4]. In industrial practice, this sensitivity has contributed to the increasing use of 100% end-of-line NVH testing for gears and e-axles in order to detect acoustically relevant anomalies before vehicle assembly [2,5].

Existing reviews have primarily addressed general EV NVH sources, such as motor noise, inverter-related excitation, or gear whine, together with broad mitigation strategies [1,6]. Other studies have focused more narrowly on nominal gear optimization, particularly the reduction in transmission error through profile and microgeometry refinement [4,7]. However, a clear gap remains in systematically capturing how manufacturing and assembly deviations propagate through the drivetrain and influence NVH response. In particular, limited attention has been given to how small deviations introduced along the rotor–shaft–gear–bearing–housing chain interact, propagate through the transfer path, and ultimately contribute to acoustic scatter across production units.

This review addresses that gap by synthesizing existing knowledge and establishing a system-level framework describing how manufacturing- and assembly-induced deviations influence excitation generation, transfer behavior, and radiated noise. The focus is placed on electric drive units and e-axles, with particular emphasis on the rotor–shaft–gear–bearing–housing system. The review considers how imbalance, run-out, bearing internal clearance, shaft misalignment, spline or pilot fit, thermal growth, and assembly phase indexing can alter the final NVH signature. The cause-and-effect sequence of interest is therefore: deviations within nominal tolerance limits → mechanical excitations (orders, transmission error, and modulation effects) → transfer through bearings and housing → radiated noise and production-level detection. Both experimental and modeling studies from 2015 to 2026 are considered, with particular attention given to recent contributions from the 2023–2026 period. This system-level sequence is summarized schematically in Figure 1.

Core research questions: The review is structured around the following questions: (1) Which manufacturing or assembly deviations are the dominant NVH drivers in EV drivetrains? (2) How do imbalance, run-out, clearance, misalignment, and spline centering errors influence specific orders, sidebands, or transmission error (TE, defined as the deviation between the actual and ideal angular position of the driven gear) and the resulting noise? (3) What role do temperature-dependent fits and preload changes play in NVH behavior? (4) How does assembly phase indexing affect final noise and vibration response? (5) Which modeling and test methods are used to study these effects? (6) Which end-of-line or in-process diagnostic techniques can detect variability-induced NVH issues in production?

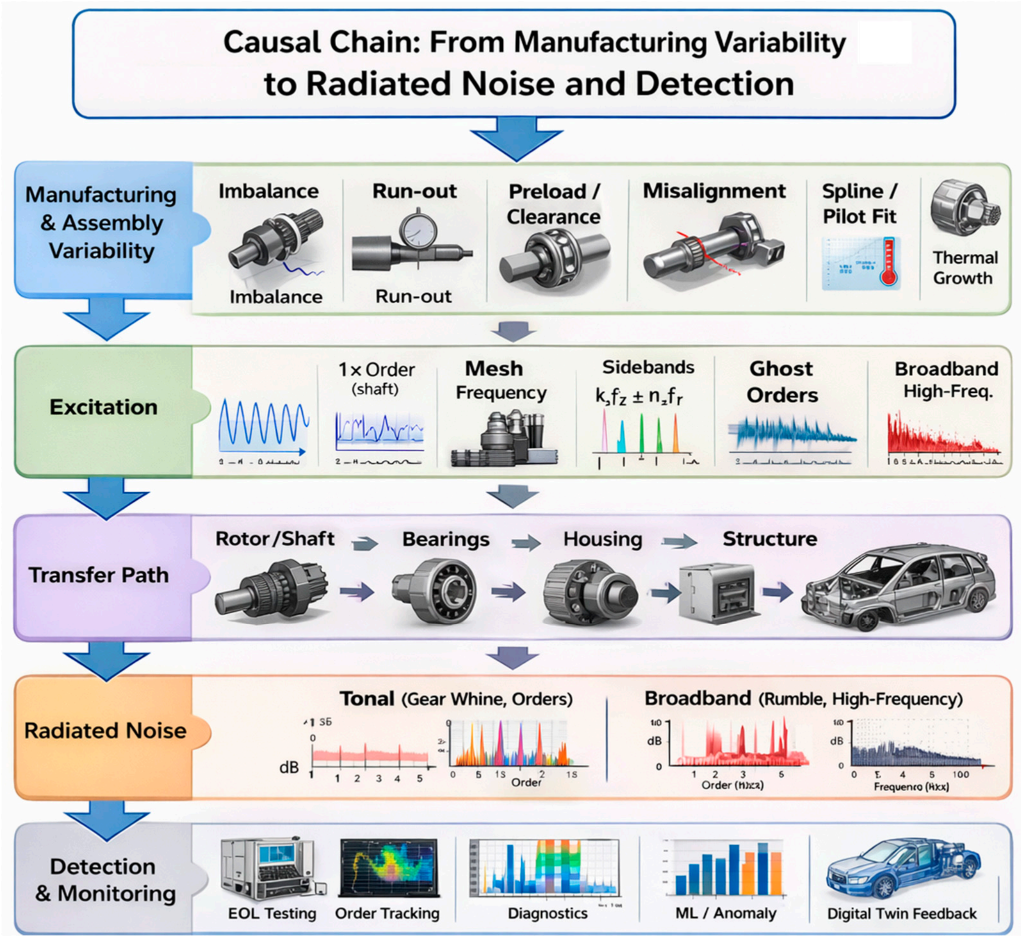


Figure 1. System-level representation of how manufacturing and assembly deviations propagate through excitation, transfer, and radiation mechanisms.

Beyond answering these questions, the present work aims to structure manufacturing- and assembly-induced NVH scatter into a coherent system-level framework and to translate this understanding into simulation-oriented engineering guidelines. Despite the increasing number of studies addressing individual NVH mechanisms, the prediction of unit-to-unit acoustic variability in electric drivetrains remains limited. Existing research typically focuses either on nominal system behavior or on isolated deviation sources, without systematically capturing how multiple small manufacturing and assembly deviations interact and propagate through the drivetrain. As a result, the mechanisms governing acoustic scatter across production units are still not fully understood, and their representation in simulation workflows remains incomplete.

The contribution of the present review is therefore twofold. First, it provides a structured, system-level synthesis of manufacturing and assembly variability, explicitly linking deviation sources to excitation mechanisms, transfer-path behavior, and radiated NVH response. Second, it translates this understanding into a variability-aware simulation framework that reflects production-representative conditions and supports robustness-oriented NVH engineering.

Scope and exclusions: The scope of the review is limited to mechanically induced excitation mechanisms in the rotor–shaft–gear–bearing system. Electromagnetic effects are considered only where they are coupled to mechanical deviations, such as rotor eccentricity affecting motor forces. Generic motor whine or gear whine studies that do not include a variability-related context are excluded. Surface micro-topography is discussed only where it contributes to assembly-related ghost orders, modulation effects, or production variability, rather than as an isolated gear-finishing topic. The emphasis is on literature published from 2015 onward, while selectively including earlier foundational work where necessary for physical interpretation. Industrial insights are included where they support or complement published findings, but are formulated in a generalized manner to ensure reproducibility and applicability.

In this work, manufacturing and assembly variability refers to source-side variation arising from production and assembly processes, whereas deviations denote specific departures from nominal geometry, position, fit, clearance, preload, or phase alignment. NVH scatter, or acoustic scatter, denotes the resulting unit-to-unit variation in noise and vibration responses across assembled units. The remainder of this review is organized as follows. Section 2 describes the literature search, screening, and thematic categorization process. Section 3 synthesizes the main manufacturing and assembly variability mechanisms and their NVH pathways. Section 4 presents a structured framework for variability-aware NVH simulation. Section 5 discusses methodological implications, remaining gaps, and future research directions, while Section 6 summarizes the main conclusions.

2. Materials and Methods

This study is a structured narrative review. To improve transparency and reproducibility, selected elements of a PRISMA-inspired workflow were adopted to document the literature search, screening, and selection process.

The methodological approach was designed to identify studies linking manufacturing or assembly deviations to NVH outcomes in electric drivetrains. The selected studies were then grouped into technically meaningful deviation categories for comparison and synthesis. It should be noted that the present review primarily adopts a mechanism-driven perspective rather than a statistical meta-analysis approach. Although the term variability is used throughout the manuscript, the focus is on physical cause–effect relationships, deviation mechanisms, and their propagation through the drivetrain NVH chain. Statistical and probabilistic modeling approaches are discussed where relevant, but a full quantitative treatment of production scatter is beyond the scope of this review.

2.1. Search Protocol

The literature identification and screening process followed a structured approach inspired by PRISMA principles to enhance transparency and traceability. The following databases were used: Scopus (Elsevier B.V., Amsterdam, The Netherlands), Web of Science (Clarivate Plc, London, UK), Google Scholar (Google LLC, Mountain View, CA, USA), and SAE Mobilus (SAE International, Warrendale, PA, USA). The search was conducted using a combination of targeted keywords and Boolean logic. The review window spans from 2015 to 2026. The review focused on English-language sources and prioritized peer-reviewed journal articles, SAE technical papers, conference papers with traceable methodology, and selected industrial publications. Industrial publications were included only when they provided sufficient technical detail, such as a clearly described measurement or simulation setup, identifiable drivetrain or component context, explicit NVH-related output metrics, and traceable authorship or institutional source. Pure marketing materials, product brochures without technical methodology, and unverifiable internal claims were excluded. The scope was limited to studies addressing manufacturing- and assembly-induced NVH scatter in EV or hybrid drivetrain systems. Studies outside this system-level context were excluded.

2.2. Search Strings and Keywords

Example combinations:
"electric drive unit" AND NVH AND "manufacturing variation"
"e-axle" AND "bearing clearance" AND vibration
"gearbox" AND imbalance AND noise
"rotor shaft" AND run-out AND NVH
"phase indexing" AND "assembly variation" AND drivetrain.

Only English-language peer-reviewed journal articles, SAE technical papers, relevant conference papers, and selected industrial technical publications were included. Industrial sources were retained only if they contained sufficient technical information to support interpretation of the reviewed NVH mechanism, rather than serving only as product descriptions or marketing material.

Studies focused purely on electromagnetic NVH, motor acoustics unrelated to drivetrain variability, or general gear whine without assembly relevance were excluded. These search strings were selected to cover the main system-level deviation mechanisms addressed in this review.

2.3. Screening and Selection Process

The screening and selection process followed a structured PRISMA-inspired workflow for transparency. Screening involved an initial review of abstracts and titles based on relevance, followed by a full-text assessment. Eligibility was determined based on relevance to EV drivetrain NVH, explicit consideration of manufacturing or assembly variability, and clarity of the underlying excitation or mechanism. The resulting screening and selection counts are summarized in Table 1.

Table 1. Summary of the PRISMA-inspired literature screening and selection process.

Stage	Count
Records identified via databases	387
Duplicates removed	74
Records screened (title + abstract)	313
Records excluded	220
Full-text articles assessed	93
Full-texts excluded	43
Studies included in review	50

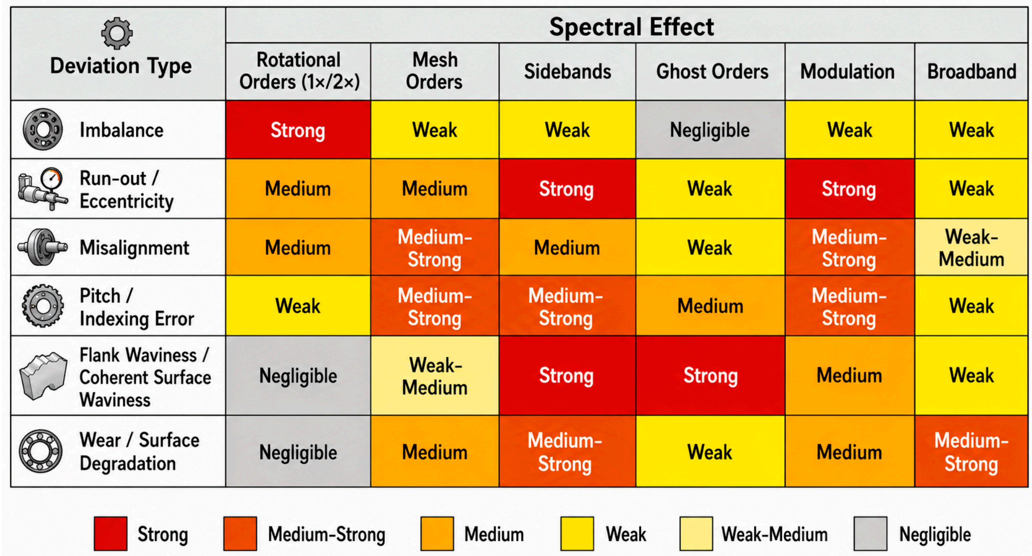
Studies were excluded if they focused exclusively on electromagnetic noise without mechanical coupling, general gear noise without variability context, or systems outside electric or hybrid drivetrains. For industrial sources, inclusion additionally required a traceable origin, technical relevance to drivetrain NVH, and sufficient methodological detail to support the stated mechanism or trend. Quantitative values from industrial sources were used only when the measurement or simulation context was sufficiently described; otherwise, such sources were treated qualitatively.

2.4. Thematic Categorization

The selected studies were grouped into eight thematic categories reflecting the dominant deviation mechanisms and their NVH pathways: Imbalance and Rigid-Body Excitation; Run-out, Eccentricity, Concentricity; Bearing Clearance, Fits, Preload; Spline and Pilot-Surface Centering; Thermal-State-Dependent Clearance Shift; Phase Indexing and Assembly Clocking; Transmission Error, Sidebands, Order Interference; and End-of-Line Diagnostics and Production Control.

These categories form the backbone of the Literature Review and allow structured comparison across methodologies, drivetrain types, and validation approaches. This thematic structure was selected because it supports synthesis not only by component type, but also by deviation mechanism and NVH pathway.

To support the thematic synthesis, Figure 2 qualitatively summarizes how the main deviation mechanisms reviewed in this paper are reflected in characteristic spectral features such as mesh-order amplification, sidebands, ghost orders, modulation, and broadband response.



Deviation Type	Spectral Effect					
	Rotational Orders (1×/2×)	Mesh Orders	Sidebands	Ghost Orders	Modulation	Broadband
Imbalance	Strong	Weak	Weak	Negligible	Weak	Weak
Run-out / Eccentricity	Medium	Medium	Strong	Weak	Strong	Weak
Misalignment	Medium	Medium-Strong	Medium	Weak	Medium-Strong	Weak-Medium
Pitch / Indexing Error	Weak	Medium-Strong	Medium-Strong	Medium	Medium-Strong	Weak
Flank Waviness / Coherent Surface Waviness	Negligible	Weak-Medium	Strong	Strong	Medium	Weak
Wear / Surface Degradation	Negligible	Medium	Medium-Strong	Weak	Medium	Medium-Strong

Figure 2. Qualitative mapping of typical gear-related deviations to their commonly observed spectral signatures. The matrix is intended as a schematic interpretation guide rather than a universal diagnostic rule, since the observed spectral response depends on operating condition, measurement type, transfer path, and structural resonance behavior. The Strong/Medium/Weak classification is based on the qualitative synthesis of the mechanisms and studies discussed in Section 3. It reflects the authors' engineering interpretation of the reviewed literature and should not be interpreted as a quantitative statistical ranking.

3. Literature Review

This section presents the reviewed variability mechanisms in a structured manner, following the thematic categorization introduced in Section 2.4.

3.1. Imbalance and Rigid-Body Excitation

Definition and context:

Imbalance refers to an uneven mass distribution causing the center of mass of a rotating component to be offset from its axis of rotation. This generates a centrifugal force at 1× rotational frequency, exciting low-frequency rigid-body modes. In electric drive units, where the drivetrain spins at high RPM and masking noise is low, even small imbalances can produce pronounced NVH issues such as cabin hum or low-frequency booming [8,9].

Imbalance is classified as either:

Static imbalance: where the mass offset lies in the plane perpendicular to the rotation axis.

Dynamic imbalance: where imbalance masses lie in different planes, introducing a moment [9].

The imbalance magnitude U is typically expressed in g·mm and defined as:

$$U = m \cdot r, \tag{1}$$

where m is the mass (g) and r is the distance from the rotation axis (mm). The corresponding unbalanced force F at angular velocity ω is:

$$F = m \cdot r \cdot \omega^2 = U\omega 2, \tag{2}$$

The allowable residual unbalance is governed by ISO 21940-11:2016, which specifies procedures and unbalance tolerances for balancing rotors with rigid behaviour [10]. The broader ISO 21940 series provides the general framework for rotor balancing terminology and application [11]. For high-speed rotors in traction drive applications, balance quality targets are commonly selected using ISO 21940 methods; in practice, the required grade is application- and OEM-specific, with G2.5 often used as a reference for precision rotating components. The permissible eccentricity e (in µm) is given by [10]:

$$e = \frac{(9549 \cdot G)}{n}, \tag{3}$$

where G is the balance quality grade (mm/s), n is the rotational speed (rpm), and e is the permissible eccentricity (µm). The constant 9549 results from the unit conversion $60 \times 1000/(2\pi)$, ensuring consistency between rotational speed, balance quality, and eccentricity.

Manufacturer benchmarks:

Industrial studies and application reports indicate that EV drive rotors are typically balanced to relatively tight residual imbalance levels due to high rotational speeds and increased NVH sensitivity. Rotor–shaft assemblies are commonly balanced as a unit in two correction planes, since assembly effects can significantly influence the final imbalance state. Intermediate shafts, owing to their mass asymmetry, are generally more sensitive to imbalance than more axisymmetric rotating components. In early development phases, elevated imbalance levels are often observed, which can typically be reduced through manufacturing optimization and improved balancing procedures. In high-performance drivetrains, tighter imbalance control may be required to avoid order coincidence with other excitation sources, such as CV joint harmonics.

NVH contribution and spectral effects:

Imbalance primarily excites the 1× mechanical order. If this overlaps with housing or mount modes, it can result in audible booming or structural vibration. In PMSM motors, the 1× mechanical order is typically well separated from dominant EM orders (e.g., 6× for 3-phase, 8-pole machines), minimizing order interference—but not eliminating the NVH impact.

Horváth and Zelei highlight imbalance as a primary mechanical NVH source in EVs [1]. Klarin et al. showed that rotor imbalance amplifies the 1st order and, when combined with torque ripple, can produce beat frequencies [6]. Dewesoft d.o.o. (Trbovlje, Slovenia) field data [3] confirms that even a slight imbalance affects NVH beyond what idealized simulations predict. A case study by Lee et al. [12] showed that a rotor with axial imbalance combined with spline play produced a distinctive helicopter-like tone in the cabin. Once the system was rebalanced and reassembled, the issue disappeared [12].

Mitigation strategies:

- Precision dynamic balancing (G2.5 or better).
- Balancing in the final assembled state (e.g., rotor + shaft + gear) to account for tolerance stack-up.
- Phase indexing of components during assembly to desynchronize heavy spots (see Section 3.6).
- Avoiding tolerance stacking by using press-fit assemblies or balancing in situ.

Thelen and Burkert [13] outlined improvements in balancing machine accuracy that are now standard in EV rotor production.

End-of-line diagnostics and thresholds:

Industrial practice suggests that imbalance-induced 1× vibrations on intermediate shafts can be detected at end-of-line using dedicated signal filters, with threshold-based criteria applied for production release. Representative threshold levels are typically defined in industrial practice; however, publicly available sources rarely report specific values in detail.

Rotor and shaft imbalance is among the most common NVH drivers; however, this review highlights that its impact must be interpreted within a broader system-level variability context. Although balancing strategies and order separation are effective mitigation measures, manufacturing and assembly consistency remain critical for achieving robust NVH performance. Compared to other variability sources, imbalance represents a relatively well-understood and predictable NVH mechanism, with excitation scaling primarily with rotational speed and mass distribution. However, its interaction with other deviations, such as spline misalignment or run-out, may still lead to non-intuitive system-level responses.

3.2. Run-Out and Eccentricity Errors

Definition and context:

Run-out refers to a deviation from perfect concentricity, where the rotational axis does not coincide with the geometric center of a rotating component. In geared systems, this is typically caused by eccentric mounting, bore machining errors, or geometric imperfections of the rotating element. Rotor–stator eccentricity in electric machines and out-of-round components represent related forms of eccentricity.

In this review, run-out is used as a measurable manifestation of eccentricity, typically quantified as total indicator run-out (TIR), while eccentricity refers more generally to the geometric offset between rotational and geometric axes. Such components are often referred to as "ghost orders," meaning spectral components that do not correspond to integer multiples of primary excitation sources such as shaft or mesh orders.

Run-out introduces a once-per-revolution (1×) excitation, leading to periodic variations in gear tooth engagement, mesh force, and transmission error. Gear eccentricity and transmission error are well-known contributors to vibroacoustic excitation in drivetrain systems [14].

Two common types are defined:

- Radial run-out (static eccentricity): The geometric center of a rotating element is offset from its rotational axis but remains parallel [15].
- Dynamic run-out (tilt eccentricity): The rotational axis is angularly misaligned, producing a wobble effect.

The magnitude of run-out R is typically defined as the total indicator reading (TIR), expressed in microns, and measured on functional surfaces (e.g., gear teeth) relative to the datum axis (e.g., bore axis).

Eccentricity-related errors can significantly influence drivetrain dynamics, as they introduce time-varying forces and may amplify vibration levels, particularly when coupled with gear mesh stiffness variations and other excitation sources [15].

NVH excitation mechanism:

Run-out causes modulation of tooth mesh forces at shaft frequency (1/rev), creating sidebands around the main gear mesh frequency. These are known as "ghost orders" when they do not align with natural harmonics of gear or motor excitation [4]. For example, a gear with a single high spot induces ±1× sidebands around the mesh frequency, and if these fall into an audible range, they may produce howling or beating tones.

Transmission Error and Sideband Formation:

TE represents the deviation between the actual and ideal angular position of the driven gear and acts as a primary excitation source in geared systems. A perfectly stiff gear pair with ideal tooth geometry would yield minimal TE and produce a sharp tonal response at mesh frequency. However, real gears exhibit micro-TE fluctuations due to load, tooth compliance, and alignment errors.

As discussed earlier in this section, the spectral characteristics of transmission error depend not only on its magnitude but also on its time variation and modulation content. In particular, run-out- or eccentricity-driven modulation redistributes part of the response from the principal mesh order into sidebands around the mesh frequency, which can be especially noticeable in EV applications because of the low masking noise level [16].

Run-out contributes directly to transmission error by introducing a once-per-revolution modulation of the gear-mesh excitation. In simplified form, this modulation can be represented as:

$$\mathrm{TE(t)} = \mathrm{TE_0} + \mathrm{A_e}\ \sin(2\pi f_{shaft}\mathrm{t} + \varphi), \tag{4}$$

where TE_0 is the nominal transmission-error component, A_e is the modulation amplitude associated with eccentricity or run-out, f_{shaft} is the shaft rotational frequency, and φ is the phase angle. This sinusoidal modulation produces sidebands around the gear-mesh frequency. If f_{mesh} is the gear-mesh frequency, the resulting spectrum may contain components at $f_{mesh} \pm f_{shaft}$, $f_{mesh} \pm 2f_{shaft}$, and higher-order sidebands, which are characteristic of run-out-induced modulation.

Spectral effects:

The classic spectral signature of run-out is a pair of sidebands spaced by the shaft rotational frequency, f_{shaft}. The amplitude of these ghost orders is sensitive to both the eccentricity level and the system's transfer path. Transmission Error (TE) increases with run-out, especially if the tooth contact point shifts significantly during rotation.

Horváth et al. [17] showed that introducing a simulated pitch/run-out error into an otherwise quiet gear system generated a dominant 16.66 Hz ghost tone—corresponding to 1× shaft frequency. Their study found a tenfold increase in mean TE when a realistic indexing deviation was applied, highlighting how sensitive gear NVH is to run-out [17]. Najib et al. confirm that indexing and eccentricity errors remain a primary NVH driver and must be included in simulation models [18].

Motor rotor eccentricity:

Rotor–stator eccentricity in electric machines represents a major source of electromagnetic excitation and can significantly influence NVH behavior. Eccentricity leads to asymmetry in the air-gap magnetic field, generating additional force harmonics and vibration components.

Both static and dynamic eccentricity can introduce additional electromagnetic force orders that may couple with structural modes of the stator and housing, thereby amplifying vibration and noise.

However, the resulting NVH response is not always proportional to the eccentricity magnitude. The structural dynamics of the motor housing and stator can act as a filter, meaning that only certain excitation orders are efficiently transmitted and radiated as noise. This leads to a nonlinear relationship between eccentricity and perceived NVH, where increases in excitation do not necessarily result in proportional increases in radiated noise.

As a result, controlling rotor eccentricity is important not only to reduce excitation levels but also to avoid the coincidence of electromagnetic force harmonics with structural resonances, which can lead to pronounced tonal noise [19].

Manufacturing tolerances and typical values:

Tight control of run-out and eccentricity is essential in EV gearboxes and electric drive units, as even small geometric deviations can generate significant dynamic excitation at high rotational speeds. Precision gears and rotor–bearing interfaces therefore require strict control of concentricity, bore alignment, and bearing seat geometry.

For high-speed rotors, the centrifugal force associated with eccentricity follows the same relationship as given in Equation (2), where the force scales with mass, eccentricity, and the square of angular velocity. As a result, even micrometer-level eccentricity can lead to substantial 1× shaft-order excitation due to the quadratic dependence on rotational speed. Such excitation may produce noticeable housing vibration if it coincides with structural sensitivity or resonance conditions [20,21].

Assembly sensitivity and error stacking:

Assembly interfaces can either amplify or reduce run-out depending on how concentricity is defined across mating features. In particular, the interaction between spline centering and pilot centering can create an unintended offset when both features simultaneously constrain radial position. A common design approach is therefore to define a single master centering feature, while the secondary interface is relieved sufficiently to avoid over-constraint. This helps ensure deterministic alignment and reduces tolerance stack-up risk.

Measurement and detection:

Run-out is routinely inspected via total indicator run-out (TIR) measurements. Gear accuracy classes are used in practice to define class-specific limits, and EV gearboxes often demand one grade better than traditional ICE counterparts, effectively halving allowable run-out [2]. End-of-line single-flank tests can detect sinusoidal TE indicative of run-out. Marposs S.p.A. (Bentivoglio, Italy) [22] reports that integrating EOL TE testing with order-tracking allows early rejection of parts with ghost order risk.

Mitigation strategies:

Effective mitigation includes minimizing bore-tooth misalignment during manufacturing, applying tight concentricity control to pilots and shafts, avoiding redundant centering features, and balancing rotor–shaft assemblies in their final installed configuration so that interface stack-up effects are included in the final state. These mechanical measures are consistent with established drivetrain NVH practice, where excitation reduction must be addressed together with structural response control [18,20,21]. For electric-machine-related eccentricity, electromagnetic fault modeling provides a complementary basis for interpreting how rotor–stator asymmetries modify excitation forces and vibration response [23].

Run-out and eccentricity are well-understood NVH drivers. They cause 1/rev modulations that manifest as sidebands or ghost orders in the spectrum. These are particularly critical in EVs due to the absence of masking engine noise. Modeling techniques now incorporate run-out into TE-based risk models [24], and tolerance stack analysis reveals its interaction with mesh and housing dynamics. Maintaining tight run-out control—both in manufacturing and assembly—is therefore essential for predictable and low-noise EV drive units. In contrast to imbalance, run-out and eccentricity introduce modulation effects that are highly sensitive to system interactions, including gear mesh stiffness variation and structural transfer characteristics. This makes their NVH impact more difficult to predict and more dependent on combined tolerance conditions.

3.3. Bearing Clearance, Preload, and Fit Effects

Bearing internal clearance refers to the internal free play between rolling elements and races, whereas preload denotes an externally applied compressive force that eliminates this clearance and increases system stiffness.

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Background: Bearings support the shafts and dictate how forces are transmitted to the housing. Bearing internal clearance (the small gap between races and rolling elements when unloaded) and bearing preload (an intentional compressive load to remove that clearance) greatly influence the dynamic stiffness of the shaft-bearing system. In assembly, bearings can be mounted with either a slight clearance (endplay) or preload (using shims, wave springs, or paired arrangements). Additionally, how bearings are fit into housings and onto shafts (interference vs. slip fit) affects their effective stiffness and damping. In EV gearboxes, design trends have moved toward preloaded bearing arrangements to increase system rigidity and prevent gear mesh misalignment under load [25]. But if improperly adjusted, preload can be lost or excessive, each causing NVH issues (looseness or excessive stiffness/friction, respectively).

NVH effects: Insufficient preload or excess clearance can allow micro-movements of the shaft (microslip or "wind-up" in the bearing) that modulate gear alignment, leading to noise. As shown by multiple sources, optimizing bearing preload/clearance can yield significant vibration reductions [5]. Specifically, Hazra and Reddy (2022) reported that preload adjustment can reduce vibration levels over a broad frequency range [26]. The mechanism is that removing clearance eliminates any "backlash" or rattling between bearing components, forcing the shaft to act as a single continuum with the housing for small displacements.

However, too much preload can elevate bearing rolling friction and transmit high-frequency vibration (from rolling element passage or surface roughness) directly into the structure. There is a sweet spot where clearance is just eliminated and a light preload ensures stability without greatly increasing stiffness beyond necessity [27]. Bal et al. (2022) demonstrated this experimentally: raising preload reduced the specific bearing frequencies' amplitudes (the so-called ball-pass or cage frequencies) [27], but beyond a point, further preload gave diminishing returns and potential other issues like heat.

Case study—bearing endplay design: Pingale and Soni's 2025 SAE paper [25] provides an excellent real-world example. The baseline EV gearbox had a floating deep-groove ball bearing on one shaft (to allow thermal expansion). The clearance in that fit inadvertently let the shaft axially shift and slightly tilt under load, contributing to misalignment and gear noise [25]. By redesigning the mounting (adding a retainer plate and shimming to remove the end-float), they effectively preloaded the bearing lightly. The result was a 2–6 dB reduction in gear whine in tests [25], confirming that the previous NVH issue was largely due to tiny uncontrolled bearing movements. Interestingly, this design change also improved load distribution in the housing and bearing life [25]—a win-win for NVH and durability.

Fit and centering: Bearing outer race fits in the housing (tight vs. loose) can also matter. A loose fit might allow the outer race to spin or fret (leading to noise called "creep" or "fretting corrosion" noise). A very tight interference fit, on the other hand, can distort the race shape (influencing internal clearance) and potentially induce vibration if the distortion is uneven. Liu et al. (2023) studied gear-shaft interference fits and noted that heavy interference pre-stresses the gear and bearings, altering meshing characteristics [28]. If the interference is too high, it can reduce bearing internal clearance to zero (or even negative—creating built-in preload). Some modern gearboxes use selective fits, e.g., a slight interference on the rotating ring of a ball bearing (to prevent spinning) but a slip fit on the stationary ring combined with a spring to set preload. This avoids unwanted stress while ensuring the bearing stays put.

Manufacturing and assembly considerations: Achieving the correct preload often relies on selective shims or collapse spacers. Manufacturing variability in housing and shaft lengths can cause preload variation from unit to unit. For example, a housing bearing a few microns out of spec could result in a bearing outer race not seating fully, thus changing preload. In production, end-of-line checks like torque-to-turn or acoustic checks are used to verify proper preload (an overly preloaded bearing often emits a growling noise or has higher drag torque). Some OEMs have introduced active adjustment, e.g., threaded collars that are tightened to a torque corresponding to the desired preload, compensating for tolerance stack-up.

From a NVH quality perspective, insufficient preload or unexpected clearance can result in bearing noise—often perceived as a rough growl or inconsistent tone, especially under coast-down or lightly loaded conditions. Bučinskas et al. (2010) observed that bearings with greater internal clearance produced higher tonal components at bearing-related rotational frequencies [29]. In EV drive units, one observed phenomenon is a faint "swish" or rumble at certain speeds due to slight roller agitation when unloaded; applying a small preload tends to quell this.

Guidelines: The collected research and practice suggest these guidelines: (a) Use preload in moderation—just enough to remove clearance. (b) If thermal expansion will reduce preload (as parts grow), design the cold preload slightly higher so that at operating temperature, it does not drop to zero. (c) Avoid uncontrolled end-floats; if some float is needed for thermal reasons, consider spring preloading (wave springs are commonly inserted to maintain some force over expansion). For instance, wave springs can provide a consistent axial force to a bearing pair, accommodating thermal growth while maintaining contact [30]. (d) Ensure consistent fits—e.g., if a bearing outer race is meant to be tight, maintain surface finish and diameter tolerances on the bore to avoid micro-slip, which can cause noise.

Bearings are not just passive supporters; their assembly state is central to NVH outcomes. Reducing clearance and applying the correct preload have been empirically shown to reduce vibrations significantly [5]. As EV NVH engineering advances, bearings are being treated as tunable elements, with some considering adaptive or smart bearing preload devices (though mostly in research). The key is consistency: variability in preload from one unit to another can lead to NVH scatter (some vehicles are quiet, some with slight bearing hum). Thus, precise control and verification of bearing preload during assembly is an emerging focus in quality control for EV drive units. Compared to geometric deviations, bearing-related variability acts primarily through changes in system stiffness and constraint conditions. This makes preload and clearance particularly influential, as they can either stabilize or amplify other excitation mechanisms depending on the assembly state.

3.4. Spline Coupling and Pilot Surfacing Effects

Many electric drivetrains connect the motor shaft to the gearbox via a spline coupling. Spline couplings allow torque transfer with some misalignment tolerance and axial sliding, but they also introduce backlash, potential eccentricity, and centering uncertainty. In practice, this makes the spline–pilot relationship particularly important, because if both interfaces attempt to define concentricity simultaneously, small tolerance mismatches may introduce static eccentricity, unintended preload, or run-out-like excitation.

More relevant here are continuous noises such as the spline rumble described by Choi et al. (2023) [31]. They traced a cabin-droning noise to the spline coupling between the motor and gearbox [31]. Their analysis showed that spline pitch error and shaft misalignment generated a periodic radial force in the spline, which excited a structural resonance and produced a low-frequency rumble. By improving spline machining and aligning the motor and gearbox spigot more precisely, the rumble was resolved [31]. This is particularly important because the mechanism arose from relatively small manufacturing and assembly deviations rather than from gross failure.

McKenny's analysis further explains how a spline can influence radial centering rather than merely transmit torque [32]. Depending on spline geometry, contact stiffness, and friction conditions, the interface may either help center the shafts or create asymmetric contact that competes with the intended pilot-based alignment [32]. This supports the interpretation that spline–pilot interaction can become a source of run-out-like excitation and an underexplored contributor to EV drivetrain NVH scatter.

The broader design implication is that centering hierarchy should be clearly defined. If spline fit errors, backlash, or misalignment are not controlled, the spline may partially override pilot-based concentricity and contribute to impulsive or tonal NVH behavior. This is consistent with the broader modeling direction in which spline-induced misalignment and run-out are already treated as relevant inputs in tolerance-based TE prediction workflows [24]. Overall, the available literature remains limited, but it suggests that spline coupling can become a significant variability driver once gears and bearings are already well optimized. More generally, gearbox vibration studies show that dynamic responses are highly sensitive to deviations and fault-related excitation mechanisms, supporting the need to consider such effects in system-level NVH analysis [33].

Compared to more established NVH drivers, spline-related effects remain less systematically studied, yet the available evidence suggests that they can become dominant once gear and bearing-related excitations are well controlled. Their sensitivity to assembly conditions and interaction with centering features makes them a critical, but often underestimated, source of variability.

3.5. Thermal Effects on Clearance and NVH

Bearing internal clearance is influenced not only by manufacturing tolerances but also by thermal effects during operation. Changes in temperature can alter bearing clearance and preload, which in turn affect the dynamic behavior of the drivetrain. For example, experimental studies show that bearing clearance can decrease rapidly during operation and is strongly dependent on both initial clearance and ambient temperature [34].

When clearance is too large, shafts may exhibit increased radial or axial motion, leading to misalignment of meshing components and increased transmission error, which is a primary driver of gear whine [35]. Excessive clearance may also result in micro-impacts or unstable rolling conditions within the bearing, particularly under low-load conditions.

Conversely, excessive preload increases contact forces and friction, which can elevate heat generation and facilitate the transmission of high-frequency vibration into the housing structure. While increased preload may improve vibration refinement in some cases, it typically comes at the cost of efficiency and thermal loading [36].

As a result, there exists a relatively narrow "optimal clearance corridor," within which both NVH performance and durability are acceptable. However, tolerance stack-up in shafts, bearings, and housing components may shift the system into non-optimal regions. Thermal expansion further complicates this behavior, as differential expansion between materials (e.g., aluminum housings and steel shafts) alters both radial and axial clearances during operation.

In electric drive units, thermal loading originates from both the electric machine and the gearbox. As temperature increases, changes in bearing stiffness and deformation can significantly influence system dynamics, potentially introducing nonlinear vibration behavior. At the same time, lubricant properties such as viscosity and damping are strongly temperature-dependent, further modifying vibration transmission and excitation mechanisms [37].

Consequently, NVH behavior can vary significantly between cold-start and thermally stabilized operating conditions. In practice, gear whine may either decrease as lubricant viscosity reduces with temperature or increase due to changes in clearance, preload, and structural coupling. More generally, thermal effects can alter bearing stiffness, mesh constraints, and resonance alignment, thereby changing the system's sensitivity to tonal excitation. This highlights the importance of evaluating NVH performance across the full thermal operating range rather than relying solely on nominal conditions.

The conceptual effect of temperature-dependent fit and preload evolution on stiffness and order-related NVH behavior is illustrated in Figure 3.

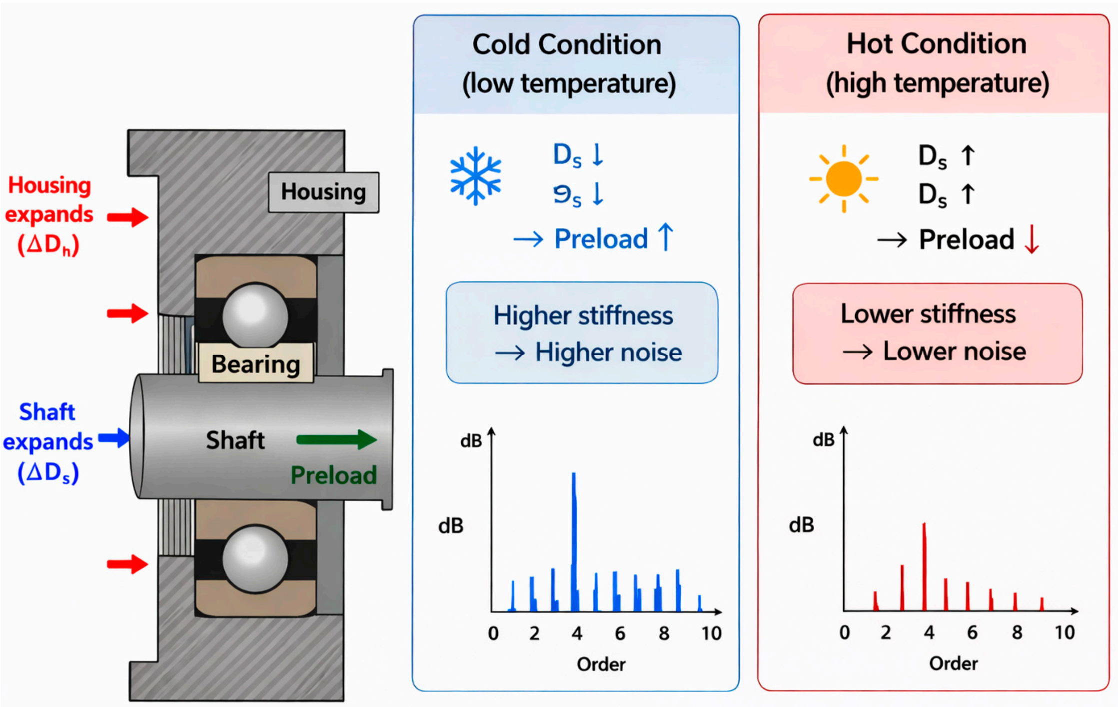

Figure 3. Conceptual effect of thermal operating state on bearing fits, preload, structural stiffness, and order-related NVH response.

A particularly important mechanism is the temperature-dependent evolution of preload. In systems using wave springs or preload spacers, thermal expansion may reduce preload force and permit slight gear misalignment, thereby increasing tonal noise. Conversely, if the thermal growth of the shaft–bearing–housing system increases preload, the assembly may become over-constrained at elevated temperature, which can promote higher-frequency vibration or bearing-related noise. Temperature, therefore, acts not merely as an operating condition, but as a modifier of the effective tolerance and constraint state of the assembled drivetrain [34,36].

Few published studies directly quantify NVH as a function of temperature, which remains a clear gap in the literature. Kim et al. (2024) developed a thermo-mechanical model for EV drive shafts, focusing on constant-velocity joints, and showed that simulations without thermal coupling may fail to capture relevant behavior [38]. Although their study was not primarily NVH-focused, it supports the broader conclusion that temperature-dependent deformation can modify contact conditions and stiffness distributions in ways that are highly relevant to drivetrain noise and vibration. A fully coupled NVH model would therefore need to account for how thermal rise changes gear mesh alignment, bearing stiffness, and structural transfer characteristics over time.

From an industrial standpoint, temperature-dependent NVH sensitivity is a well-known practical phenomenon, even if it remains only partially captured in the open literature. The appearance of a pronounced NVH issue exclusively in cold or hot operating conditions often indicates that the assembled system is sensitive to thermally induced shifts in clearance, preload, or alignment. This is especially relevant because end-of-line evaluations are usually performed close to ambient conditions; as a result, thermally activated NVH issues may escape detection unless they are considered proactively in the tolerance design process or validated under conditioned thermal operating states [34,36].

Designing for thermal extremes is therefore essential. Compatible material choices, preload strategies that remain stable across temperature, and thermo-mechanical simulation support can all help reduce sensitivity to thermal drift. Some manufacturers also use hot-condition dynamometer validation to ensure that NVH performance remains acceptable after the drivetrain reaches thermal equilibrium. Overall, temperature-dependent NVH scatter remains underexplored in the literature, but it is clearly relevant in practice. Because it links structural, thermal, tribological, and acoustic behavior, it should be treated as an important research gap in future EV drivetrain NVH studies [38].

Thermal effects differ from other variability sources in that they evolve during operation, dynamically modifying clearance, preload, and alignment conditions. As a result, their NVH impact is inherently state-dependent and may not be captured by conventional room-temperature evaluation or nominal simulation approaches.

3.6. Assembly Phase Angle (Indexing/Clocking)

Assembly phase indexing, often referred to as clocking, describes the relative angular orientation at which rotating components are assembled. In multi-stage drivetrains, this phase relationship influences how periodic excitation sources from different components interact and superpose in the assembled system.

Even when individual components meet their tolerance limits, their relative phase alignment can significantly affect the resulting vibration and acoustic response. Studies on multi-stage gear systems show that phase configuration between stages can alter the dynamic response and vibration characteristics, including the amplitude and distribution of excitation orders [39].

Similarly, in systems with multiple periodic excitation sources, such as planetary gear sets, phase relationships can lead to constructive or destructive interference, enhancing or suppressing specific vibration components [40].

As a result, the assembled system may exhibit different tonal behavior depending on the angular indexing of components, even if the underlying geometric deviations remain unchanged. In some cases, unfavorable phase alignment can amplify specific orders or produce additional modulation effects, while favorable alignment can partially cancel them.

From an NVH perspective, this highlights that assembly phase should be treated as a controllable parameter rather than a purely incidental outcome of assembly. Proper indexing strategies can therefore be used to reduce tonal response or avoid the coincidence of excitation sources with structural resonances.

The underlying mechanism is consistent with classical gear-dynamics theory. Kahraman and Vijayakar showed that the phasing of multiple transmission-error contributions can either amplify or reduce the resulting dynamic response, depending on the relative phase of the error harmonics [41]. Although this concept was originally developed in a broader gear-dynamics context, it is directly relevant to electric drivetrains, where the absence of masking engine noise makes such superposition effects more audible.

Practical evidence suggests that assembly phase can influence measured NVH. Re-indexing of rotating components may change the phase relationship between periodic excitation sources from different stages, thereby modifying how these contributions combine in the assembled drivetrain. As a result, the radiated or cabin noise response can change even when the nominal transmission-error level of the individual components remains essentially unchanged. This is consistent with the broader literature showing that phase configuration can alter the vibration response of multi-stage transmissions and that phasing effects may enhance or suppress specific excitation components [40,42].

Figure 4 schematically illustrates how in-phase and out-of-phase alignment of tooth-error patterns can increase or reduce the superposed transmission-error amplitude and the resulting order content.

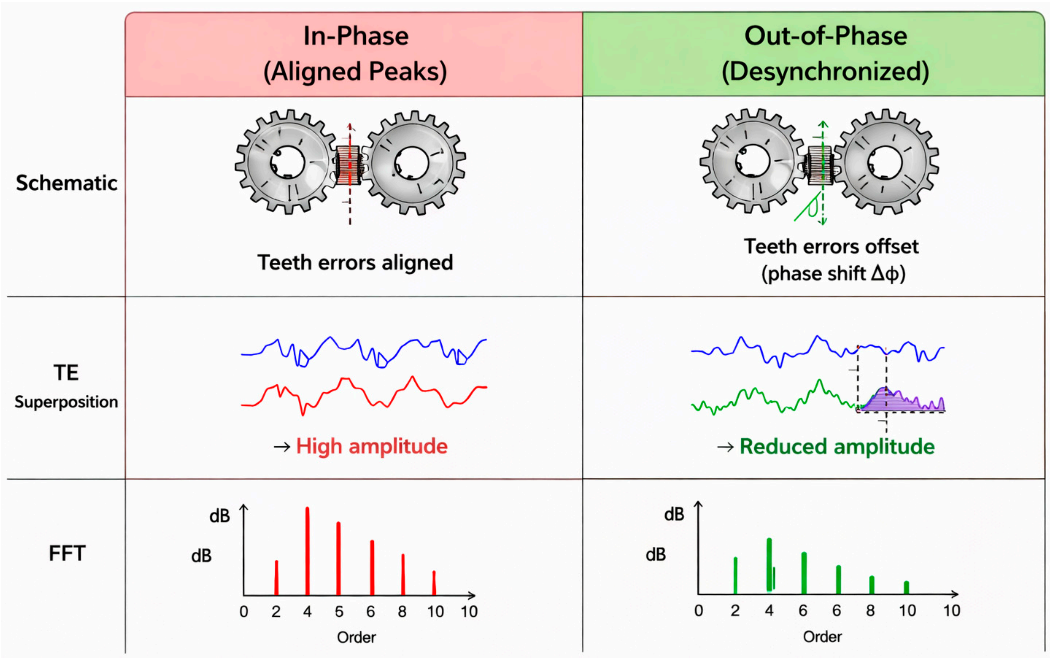

Figure 4. Conceptual influence of assembly phase indexing on transmission-error superposition and resulting order content in electric drivetrain gears.

Phase Interaction and Repositioning Logic:

Assembly-phase indexing exploits the vector nature of imbalance and geometric run-out. Each imbalance can be represented as a rotating vector (phasor), characterized by both magnitude and angular position. When multiple rotating components (e.g., rotor, gear, shaft) are assembled, their individual imbalance vectors combine vectorially, leading to either constructive or destructive superposition of excitation.

This concept is consistent with established observations in multi-stage and planetary gear systems, where phase relationships between periodic excitations influence vibration amplitude and distribution [39,42].

If a given component produces elevated NVH in a particular angular orientation, rotating it by 180° shifts its imbalance vector by π radians, which may partially or fully cancel dominant excitation components. This effect is most pronounced when the system response is governed by a single dominant order, such as the $1\times$ rotational frequency.

In practice, assembly-phase adjustments are often observed to influence NVH significantly. Re-indexing components can reduce tonal excitation by modifying the phase relationship between contributing sources, even when the individual component quality (e.g., transmission error or imbalance magnitude) remains unchanged.

While random phase assembly can lead to substantial unit-to-unit NVH scatter, controlled phase strategies can reduce this scatter and improve robustness. In some industrial applications, components may be phase-indexed during assembly or end-of-line evaluation in order to identify angular configurations associated with reduced vibration or tonal noise.

From a system perspective, assembly phase can therefore be interpreted as a hidden tuning parameter that governs how multiple excitation sources combine and propagate through the drivetrain.

Overall, assembly phase angle remains less systematically studied than run-out, preload, or misalignment, particularly in high-speed EV drivetrains. However, the available theoretical and industrial evidence suggests that clocking can become a meaningful secondary NVH tuning parameter and deserves more explicit treatment in future variability studies [41].

Unlike most geometric deviations, assembly phase does not introduce new excitation sources but alters the superposition of existing ones. This makes it a unique variability parameter, capable of both amplifying and mitigating NVH response without changing individual component quality.

3.7. Transmission Error, Sidebands, and Order Interference

Understanding mechanical orders and order tracking:

Mechanical NVH signals in rotating drivetrains are commonly evaluated in the order domain, where an order denotes a frequency component proportional to shaft rotational speed. Thus, the 1× order corresponds to the fundamental shaft frequency, 2× to twice the rotational speed, and higher orders to higher harmonics. In this framework, imbalance typically excites the 1× order, whereas gear meshing generates substantially higher mesh-related orders. Additional modulation effects, for example, those caused by run-out or eccentricity, appear as sidebands around the dominant mesh components [43,44].

Order-tracking methods synchronize the vibration or acoustic signal with rotational speed, making it possible to distinguish speed-dependent tonal components from broadband or non-synchronous content. This is especially important in EV drivetrains, where the reduced masking noise makes mechanical orders and their modulation products more perceptible [44]. Identifying characteristic orders, such as 1×, 2×, the main mesh order, and mesh sidebands, helps trace the excitation back to likely physical sources including imbalance, eccentricity, transmission error, and tooth-related modulation [45].

Transmission error as the key excitation variable:

Transmission error (TE), introduced earlier in Section 3.2, is one of the main internal excitation variables linking manufacturing deviations to tonal NVH behavior in geared systems. In electric drivetrains, its importance is amplified by the low masking-noise environment, which makes gear-related tonal excitation more directly perceptible [45].

Beyond its basic definition, TE also acts as a linking variable between manufacturing variability and radiated NVH. Variations in gear microgeometry, run-out, eccentricity, and alignment do not affect the acoustic response independently. Instead, they are combined into the TE waveform, which determines the excitation spectrum transmitted through the drivetrain. As a result, even small geometric deviations can produce pronounced tonal peaks or sidebands when they introduce periodic components into the TE signal, particularly near dynamically sensitive orders [44,45].

A key phenomenon in this context is the generation of sidebands and so-called ghost orders. These components are particularly relevant in EV applications, where narrow-band tonal features strongly influence perceived sound quality. Zhang et al. demonstrated that dynamic transmission-error measurement can be used to identify TE-related spectral components and their relationship to measured noise spectra [46]. Beyond purely mechanical TE-related excitation, spectral interaction with electrically induced harmonics is also relevant in electric powertrains. Sarrazin et al. showed that different inverter PWM control schemes can modify the noise signature of electric powertrains, which is important when inverter-related harmonics overlap with gear-mesh orders, shaft orders, or sideband components [47]. Similarly, Horváth and Kaszab introduced a tolerance ranking index (TRI) approach to quantify the contribution of individual manufacturing parameters to tonal noise risk, demonstrating that different error sources can be prioritized based on their impact on the TE-related excitation spectrum [48].

An additional complexity arises from order interaction and spectral overlap. In real drivetrain systems, multiple excitation sources—including different gear stages, shaft orders, and electromagnetic motor harmonics—can interact. When their frequencies align or fall within the same structural amplification range, constructive interference may occur, leading to increased tonal prominence. Conversely, unfavorable phase relationships or frequency separation may reduce the perceived noise level.

From a system-level perspective, this means that NVH behavior cannot be predicted solely from individual component quality metrics. Instead, the combined spectral structure of the excitation, including TE harmonics and sidebands, must be considered together with the structural transfer path. This highlights the need for integrated modeling approaches that link manufacturing variability, TE generation, and system-level dynamic response.

Overall, TE and its spectral characteristics form the central connection between geometry, excitation, and perceived noise in EV drivetrains. While significant progress has been made in measuring and modeling TE, the interaction between multiple excitation sources and their combined effect on tonal NVH remains an active research area, particularly in high-speed electrified powertrains [46–48].

Transmission error acts as a unifying variable that integrates the effects of multiple deviation sources into a single excitation signal. This makes it particularly valuable for NVH analysis, but also highlights that similar TE levels may still lead to different acoustic responses depending on spectral content and transfer-path characteristics.

3.8. Production NVH Testing and Quality Control

Production-level NVH testing plays an increasingly important role in electric drivetrain manufacturing, where tonal noise components are highly perceptible and customer expectations are stringent. As a result, many manufacturers have adopted end-of-line (EOL) acoustic testing to ensure that each unit meets defined NVH criteria before delivery.

Modern EOL testing systems typically evaluate vibration or noise signals using order analysis, spectral metrics, or band-limited indicators. These methods allow the detection of tonal components associated with gear-mesh excitation, imbalance, or structural resonance. In recent years, data-driven approaches have also been introduced, enabling anomaly detection and pattern recognition based on large datasets of production measurements [48].

Industrial studies indicate that EOL NVH signals can often be correlated with upstream manufacturing parameters, such as gear microgeometry, bearing preload, or assembly alignment. This creates the possibility of linking acoustic quality metrics to specific process variations and identifying root causes of variability. In this context, machine learning methods are increasingly used to establish relationships between production data and measured NVH behavior [48].

The broader production workflow linking end-of-line measurement, data aggregation, root-cause analysis, and digital-twin-based feedback is summarized in Figure 5.

In addition to end-of-line testing, component-level quality control remains essential for early NVH risk detection. Methods such as single-flank testing, TE measurement, surface inspection, and run-out assessment can reveal potential excitation sources before final assembly, enabling earlier corrective action and reducing the risk of downstream acoustic failures. However, routine EOL NVH tests are usually performed at fixed operating points and near ambient conditions, which means that load-dependent or temperature-dependent noise mechanisms may remain undetected. For this reason, production testing should be complemented by simulation and validation under representative operating states [34,48].

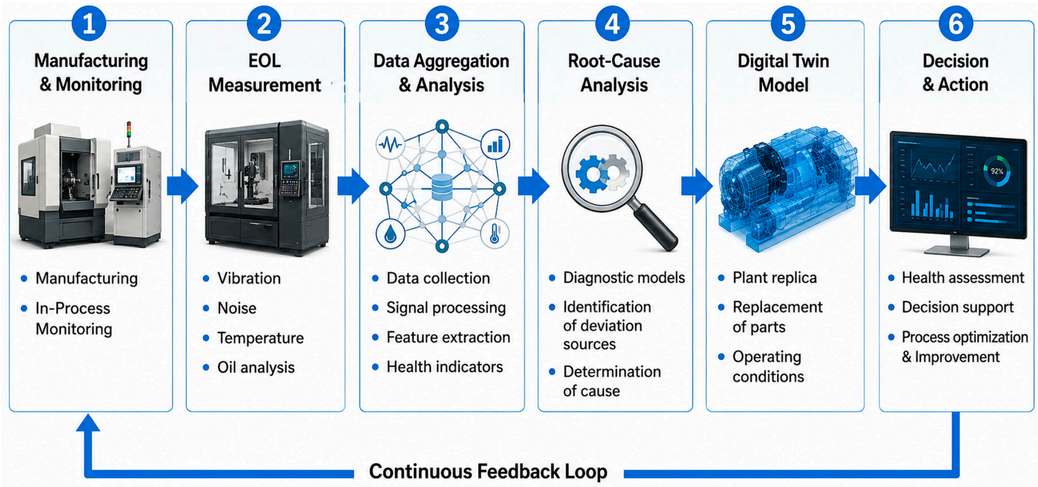

Figure 5. End-of-line measurement and digital-twin feedback pipeline for variability-aware NVH monitoring, diagnosis, and process improvement in electric drivetrains.

EOL NVH Detection and Filter Logic:

At the end of the manufacturing line, electric drivetrain units are commonly evaluated for NVH anomalies using sensor-based monitoring systems. Typical setups employ accelerometers or microphones mounted near the housing, combined with order-tracking techniques synchronized to shaft speed. These systems enable the identification of speed-dependent excitation components across a wide frequency range and allow separation of characteristic mechanical orders such as imbalance (1×), gear mesh orders, and modulation sidebands [43,49].

Advanced EOL systems increasingly incorporate signal-processing strategies designed to isolate abnormal excitation patterns. In some industrial implementations, filtering approaches are used to suppress known dominant components, such as gear mesh orders, while enhancing sensitivity to anomalies, including unexpected sidebands or low-frequency imbalance signatures. In some industrial implementations, modulation effects associated with run-out or eccentricity are identified through sidebands around mesh orders, and filtering strategies may be applied in these regions to improve sensitivity to periodic geometric deviations [4,45].

When specific interference mechanisms are known, such as order coincidence between shaft-related excitations and other driveline sources, dedicated detection logic can be implemented to target these conditions. In such cases, units exceeding application-specific predefined thresholds—typically based on order amplitude, vibration level, or spectral indicators—are flagged for further inspection or rejection.

Overall, production NVH testing forms a critical link between manufacturing variability and perceived acoustic quality. However, its effectiveness depends on the correct interpretation of measured signals in relation to the underlying physical excitation mechanisms.

Looking ahead, increasing attention is being given to integrating EOL testing with simulation-based approaches and digital twin frameworks. Such methods enable the correlation of measured data with physics-based models and support predictive diagnostics and more robust control of NVH scatter in electric drivetrains [50].

While end-of-line testing provides an effective means of detecting NVH anomalies, it remains inherently reactive and dependent on predefined thresholds. Its effectiveness, therefore, depends on the extent to which the underlying variability mechanisms are understood and anticipated during the design phase. The main studies reviewed in this section are summarized in Table 2 according to drivetrain setup, deviation type, method, NVH metric, key finding, and validation relevance.

Table 2. Representative literature on manufacturing- and assembly-induced NVH scatter in electric drivetrains (2015–2026). Sources are grouped by primary deviation type.

Ref. (Year)	Drivetrain/Setup	Main Deviation(s) Examined	Method (Sim/Test)	NVH Metric(s)	Key Finding(s)	Validation & Relevance
Horváth & Zelei (2024) [1]	EV powertrain (motor + 2-stage gearbox)	General survey of NVH issues including shaft imbalance, misalignment, gear defects	Review (literature)	–(qualitative)	Identifies shaft imbalances, gear misalignments, and assembly faults as significant contributors to EV NVH [1]. Emphasizes need for system-level modeling.	Synthesis of recent research; highlights industry trend toward tighter tolerances and holistic NVH analysis.
Hua et al. (2023) [5]	BEV powertrain (review)	Bearing quality (P0 vs. P5), preload, fit clearance	Review + some test data	Bearing vibration (accel.)	The study summarizes evidence that bearing precision class, preload, and fit clearance can substantially influence vibration levels in BEV powertrains [5].	Summarizes multiple studies; uses test data from industry. Stresses importance of bearing tolerance control for EV NVH.
Imbalance & Rigid-Body Mass Excitation						
Dewesoft d.o.o. (Trbovlje, Slovenia) (2025) [3]	e-motor on bench (example)	Rotor mass imbalance; stator misalignment	App note (test & sim)	Vibration, noise qualitatively	Even slight rotor imbalance or stator offset can measurably increase overall vibration and noise [3]. Recommends combined electrical + mechanical testing to catch such effects.	Industrial case insight; highlights need to validate simulations with physical tests for imbalance issues.
Lee et al. (2022) [12]	EV drivetrain test rig (OEM study)	Spline quality, axial imbalance (rotor axial offset)	Testing (vehicle component)	"Impact noise" level (cabin)	Found poor spline machining combined with rotor axial imbalance led to clonks ("rumble") on torque transients. Improving spline concentricity eliminated the impact noise (case study).	Industrial case example (reported in technical literature). Confirms interaction between spline error and rotor balance on impulsive NVH.
Klarin et al. (2025) [6]	2-stage EDU (AVL List GmbH (Graz, Austria) simulation)	Rotor unbalance, shaft tilt, motor torque ripple (alongside gear tolerances)	Transient 3D MBD (elastic)	Order spectra (gear mesh & 1×)	Developed high-fidelity model capturing unbalance, misalignment, and electrical orders. Unbalance mainly excited 1× shaft orders; model separated mechanical vs. motor orders in spectrum [6].	Validated model on test data qualitatively. Shows feasibility of simulating imbalance effects in large DoE for virtual EOL testing [6].
Run-out/Eccentricity (Concentricity Errors)						
Müller et al. (2025) [7]	e-motor + gearbox (RWTH Aachen)	Rotor–stator static eccentricity (motor rotor not centered)	eMBS simulation (elastic bodies + electromagnetic forces)	Acceleration (dB) and orders	Motor static eccentricity drives a strong 36th-order motor tone (from electromagnetic forces). Varying eccentricity amplitude only changed vibration by <1.5 dB [7], as housing's symmetric modes dominated response. Suggests housing redesign to break symmetry for NVH benefit.	Simulation-only study (no test validation). Industrially relevant for understanding motor manufacturing tolerances (bearing seat eccentricity) [7]. Indicates diminishing returns of ultra-tight rotor concentricity beyond a point.
Najib et al. (2025) [18]	Spur & helical gear drives (review)	Gear pitch error, run-out, misalignment (and other tolerances)	Literature review	TE, noise (various studies)	Comprehensive review concludes that manufacturing tolerances (incl. eccentricity/run-out) significantly affect gear whine and sidebands [18]. Recommends accounting for pitch/run-out errors in robust gear design.	Peer-reviewed review (IMechE). Synthesizes ~138 refs. Underlines need for tolerance consideration in CAE, aligning with industry robust design practices.

Table 2. *Cont.*

Ref. (Year)	Drivetrain/Setup	Main Deviation(s) Examined	Method (Sim/Test)	NVH Metric(s)	Key Finding(s)	Validation & Relevance
Horváth et al. (2025) [17]	Gear pair (MBD model with scans)	Tooth spacing error (indexing) as run-out-like excitation	Simulation (MSC Adams (MSC Software, Newport Beach, CA, USA) with measured errors)	Transmission Error; FFT orders	Adding a realistic pitch error map increased mean TE and introduced a distinct low-frequency "ghost" tone corresponding to the shaft order [17]. Combined microgeometry and pitch error increased peak-to-peak TE, showing nonlinear interaction effects [17].	Validated vs. bench TE measurements (good match for sidebands) [17]. Supports that even tiny indexing errors can generate new orders, emphasizing manufacturing control.
			Bearing Clearance, Preload, and Fits			
Pingale & Soni (2025) [25]	2-stage BEV gearbox (Divgi TorqTransfer Systems Ltd. (Pune, India))	Bearing axial retention & endplay (design of bearing locks vs. float)	Sim (Romax MASTA (Romax Technology Ltd., Nottingham, United Kingdom)) + Test (dyno NVH)	Mesh order SPL (dB); TE (µm)	Altering the bearing mounting to eliminate excess float yielded 2–6 dB reduction in tonal gear whine. Simulation predicted reduced transmission error and misalignment, and testing confirmed whine reduction. Also improved bearing load distribution (25% damage life increase) [25].	OEM case study with full prototype validation. Shows large NVH gains from a relatively simple assembly change (bearing preload via retainer plate)—high industrial impact for quiet gearboxes.
Bal & Ates (2022) [27]	Rigid shaft on ball bearings (lab rig)	Bearing preload levels (varied via spring or shims)	Hybrid: Nonlinear dynamic model + experimental validation	Bearing forces; shaft vibration spectrum	Increasing preload significantly attenuated the bearing's "variable compliance" vibration peaks (related to roller passing frequency) [27]. Too low preload led to looseness and peaks in vibration spectra; optimal preload shifted natural frequencies upward out of sensitive range.	Academic study, but with real bearing tests. Validates the concept that proper preload tuning can reduce vibration by stabilizing the bearing–shaft system. Relevant to setting preload in EV gearboxes for NVH.
Bučinskas et al. (2010) [29]	Gearbox (theoretical & exp.)	Bearing manufacturing class and internal clearance	Modal analysis + experiments	Housing accel. (dB)	Classic study showing how lower grade bearings (more clearance) excite more noise due to roller chatter. Specifically, larger internal clearances amplified vibrations at certain shaft orders [29]. Tight-clearance or preloaded bearings damped those modes.	Though older, often cited in NVH context [12]. Supports current trend of using higher precision bearings (P5 or better) and slight preload in EV drives [29].
			Spline/Pilot Coupling and Centering			
Choi et al. (2023) [31]	EV powertrain (motor–gear spline coupling)	Spline pitch error + shaft misalignment + unbalance ("spline rumble")	MBD simulation (detailed spline model) + rig test	Spline radial force; cabin noise (rumble)	Identified spline radial force fluctuation as the root excitation of a low-frequency rumble noise in an e-axle [31]. Spline pitch indexing errors and slight angular misalignment of the spline generated a 2–3× shaft order modulation ("rumble"). A quasi-static model was used for early design, and a full time-domain MBD for validation. Adjusting spline tolerances and ensuring proper pilot centering eliminated the rumble in prototype tests.	Automaker R&D study (conference paper). Combines simulation and test to solve a real NVH issue. Demonstrates that mis-centering of spline vs. pilot can introduce new low-frequency tones. High relevance for any spline-coupled motor-gear unit.

Table 2. *Cont.*

Ref. (Year)	Drivetrain/Setup	Main Deviation(s) Examined	Method (Sim/Test)	NVH Metric(s)	Key Finding(s)	Validation & Relevance
McKenny (2019) [32]	Spline analytical model + experiments	Spline centering force & misalignment (general)	Analytical + some measurements	Load distribution; centering force	Showed that spline geometry influences radial centering: straight-sided splines provide a centering force proportional to tooth flank contact stiffness and friction angle [32]. Small-diameter splines behave differently than large ones—can seize radially if misalignment is present. Also updated Dudley's classic misalignment factors for spline size [32].	Technical article (gear industry). Not NVH per se, but provides insight that spline interfaces might "fight" with pilot bearings for centering. Implies that if both spline and pilot are rigidly fit, assembly stress or run-out can result—an underexplored NVH contributor (potential conflict of centering).
			Thermal Effects on Clearance and NVH			
Kim et al. (2024) [38]	EV constant-velocity joint (driveshaft)	Thermo-mechanical deformation (grease heating, dilation)	FEA coupled thermal-mechanical + prototype test	Torque oscillation; durability (noise not explicit)	Although focused on CV joints, showed that simultaneous thermal expansion and mechanical load can alter contact conditions in rotating joints. A 6% correlation discrepancy between simulation and test remained [38], highlighting difficulty in modeling temperature effects. Relevance to gears: as oil and parts heat, contact pattern shifts, possibly affecting NVH (though noise not measured here).	Research study, not on gears directly but analogous. Indicates the complexity of modeling thermal effects in rotating systems. Very few NVH studies incorporate full thermo-mechanical coupling—identified as a research gap for e-axles.
			Assembly Phase Angle (Indexing/Clocking)			
Kahraman & Vijayakar (2001) [41]	Compound gear train (theory)	Phasing of dual meshes (general)	Analytical (linear)	TE amplitude, tonal response	Classic gear dynamics theory showing that aligning gear mesh index can either amplify or mitigate combined transmission error depending on phase. Introduced concept of "optimal phasing" where phase difference of 180° between two mesh errors can cancel certain harmonics [41]. (Applied historically to gear rattle, but conceptually similar for whine).	Though older and not specific to EV, this provides the theoretical basis that assembly phase can alter NVH. Modern EV drive designers use this concept implicitly when aligning gear timing marks. Gap: few recent papers quantify this effect for high-speed e-drives.
			Transmission Error, Modulations, and Order Coupling			
Zhang et al. (2023) [46]	Spur gear pair on rig (high-speed)	–(measures dynamic TE directly)	Experiment (strain-gauge TE measurement up to 20 krpm)	Kinematic TE (µrad); noise spectrum	Developed a method to measure dynamic transmission error via gear tooth strain [46]. Confirmed that peak TE correlates with tonal noise levels, and sideband frequencies in TE correspond to measured acoustic sidebands [46]. Provides a diagnostic tool for identifying whether sidebands come from manufacturing error (if visible in TE) or other sources.	Useful new measurement technique for end-of-line or lab diagnostics. Industrial relevance: could detect ghost order excitations by measuring TE on test stands, preventing subjective noise issues escaping to vehicles.

Table 2. *Cont.*

Ref. (Year)	Drivetrain/Setup	Main Deviation(s) Examined	Method (Sim/Test)	NVH Metric(s)	Key Finding(s)	Validation & Relevance
Horváth & Kaszab (2025) [24]	EV gearbox (surrogate model)	15 tolerances: pitch, run-out, profile, misalignment, etc.	Data-driven modeling (random forest on 39k sims)	Kinematic TE; Tonal Risk Index (TRI)	Showed that gear transmission error (TE) is a nonlinear function of multiple tolerances with significant interactions [24]. Using machine learning, identified pitch error and run-out as the top contributors to TE. Introduced a Tonal Risk Index linking predicted TE to expected noise risk [24]. This allowed rapid evaluation of tolerance stacks without full FE solves.	Validated ML model against high-fidelity simulations and some test trends. Demonstrates emerging approach to quantify NVH robustness in design. Industrial significance: enables setting tolerance specs by directly assessing NVH risk [24].
Production NVH Testing and Quality Control						
Klarin et al. (2025) [6]	2-stage EDU (simulation study)	Production scatter in NVH (various tolerance combinations)	Large-scale virtual DoE (MBD)	Gear whine order level; spectra	Proposed a "Virtual EOL test" simulation to predict NVH scatter bands [6]. By sampling across tolerance ranges (clearances, micro-geometry, unbalance, misalignment, etc.), the model generated distributions of NVH metrics. Able to distinguish contributions of electrical vs. mechanical orders in gear whine [6]. Result: identified which tolerances combinations yield outlier noisy units, guiding tighter control where needed.	Cutting-edge approach (SAE paper). Not yet fully validated with physical production data, but concept aligns with industry's push for zero-defect NVH. Pioneering use of HPC simulations as a design for quality tool in NVH.
Hottinger Brüel & Kjær A/S (HBK; Virum, Denmark) (2025) [30]	EOL NVH test systems (industry trend)	AI-driven NVH analytics on production lines	Industry white paper	Defect classification accuracy; correlations	Describes modern end-of-line NVH rigs that perform synchronous order analysis on each unit, using machine learning to classify subtle anomalies [30]. Digital twin models are used to simulate expected "good" spectra, and deviations trigger alarms [19]. Also highlights correlation of NVH results across the production chain—e.g., linking gear inspection data, bearing press-fit data, and final NVH spectra for trend analysis [30].	Illustrative of current best practices: major OEMs now demand 100% NVH testing on e-axles [30]. The approach integrates big data and analytics to continually improve manufacturing processes (e.g., adjusting a hobbing machine if a ghost order starts trending). Shows the future: EOL NVH as both a quality gate and a feedback loop to design/manufacturing.
Marposs S.p.A. (Bentivoglio, Italy) (2025) [20]	Gear manufacturing QC (supplier app)	Single-flank test + NVH test of gears	Application note	Gear meshing noise (dB)	Emphasizes that inspecting gears solely by geometry may miss NVH-critical issues [20]. Advocates combining single-flank transmission error tests and actual noise rotation tests for each gear before assembly [20]. Found that certain micro-geometry errors (like waviness) not caught by traditional checks were revealed by noise testing individual gears.	Shows the shift in quality control: gear suppliers adding spin tests to ensure quiet gears. Direct industrial relevance—ensuring that no "noisy" gear goes into an e-axle, thereby reducing variability in final assembly NVH.

To support a more structured synthesis, the reviewed studies were additionally classified in an evidence matrix according to primary deviation source, excitation type, transfer-path depth, validation level, operating condition, and output metric (Table 3). This matrix complements Table 2 by enabling cross-comparison beyond topic grouping alone.

Table 3. Evidence matrix of reviewed studies according to deviation source, excitation type, transfer-path depth, validation level, operating condition, and output metric.

Ref.	Drivetrain/ System	Primary Deviation Source	Excitation Type	Transfer-Path Depth	Validation Level	Operating Condition	Output Metric	Practical Relevance
Horváth & Zelei [1]	EV powertrain review	Mixed mechanical deviations	Conceptual/ literature synthesis	System-level	Review-level	Broad EV operating context	Qualitative NVH mechanisms	High
Hua et al. [5]	BEV powertrain	Bearing precision, preload, fit clearance	Bearing-induced vibration	Component-to-system	Review + some test evidence	Broad operating range	Acceleration/ vibration level	High
Klarin et al. [6]	2-stage EDU	Unbalance, shaft tilt, torque ripple, tolerances	Order excitation/coupled mechanical-electrical	System-level	Simulation + qualitative test comparison	Multi-condition simulation	Order spectra	High
Najib et al. [18]	Spur/helical gear drives	Pitch error, run-out, misalignment	TE/sideband generation	Source-focused	Review-level	General	TE/noise	High
Pingale & Soni [25]	2-stage BEV gearbox	Bearing end-play/preload	Misalignment-driven gear excitation	Source + transfer	Simulation + test	Dyno/loaded operation	SPL, TE	High
Choi et al. [31]	EV motor–gear spline coupling	Spline pitch error, shaft misalignment	Radial force fluctuation/rumble	System-level	Simulation + rig test	Operating rumble condition	Cabin noise, spline radial force	High
Kim et al. [38]	EV driveshaft/CV joint	Thermo-mechanical deformation	Contact-state shift	Component/ subsystem	Simulation + prototype test	Thermal-mechanical loading	Torque oscillation/durability proxy	Medium
Kahraman & Vijayakar [41]	Compound gear train	Mesh phasing	TE superposition	Source-focused	Analytical	General	TE amplitude/tonal response	Medium
Zhang et al. [46]	High-speed spur gear rig	Dynamic TE measurement	TE-based excitation identification	Source-focused	Experimental	High-speed rig	Kinematic TE, noise spectrum	High
Horváth & Kaszab [24]	EV gearbox surrogate model	Multi-tolerance set	TE/tonal risk prediction	Source-to-system inference	Simulation/ surrogate	Large simulated dataset	TE, TRI	High
HBK [30]	EOL NVH systems	Production scatter/ anomaly detection	Order-based quality screening	Production/ system-level	Industrial white paper	EOL test conditions	Defect classification/ correlations	High
Marposs [22]	Gear QC	Gear meshing variability	Single-flank TE + spin noise	Component-level	Application note	Supplier QC	Gear noise/TE	High

To clarify the contribution of the present manuscript, Table 4 positions this review relative to prior review directions identified in the literature. The aim is not to duplicate broader EV NVH surveys, but to synthesize how manufacturing and assembly variability propagates along the excitation–transfer–radiation chain and results in NVH scatter.

Table 4. Positioning of the present review relative to prior review themes in EV drivetrain NVH.

Review Direction	Typical Focus	What Is Usually Covered	What Is Usually Missing	Specific Contribution of the Present Review
General EV NVH reviews	Broad EV noise sources	Motor, inverter, gear whine, general mitigation	Manufacturing-induced variability as a dedicated system-level problem	Focused synthesis of manufacturing and assembly variability in the rotor–shaft–gear–bearing–housing chain
Gear microgeometry/TE optimization reviews	Gear design refinement	Profile modification, lead correction, TE reduction	Assembly-driven scatter, spline/pilot interaction, preload drift, production variability	Extends the discussion from nominal TE optimization to variability-induced tonal scatter
Component-specific studies	One mechanism at a time	Run-out, preload, misalignment, or thermal effect in isolation	Cross-comparison across mechanisms and validation depth	Structured thematic comparison across eight variability categories
Industrial EOL/QC sources	Production detection	Order analysis, anomaly detection, quality control logic	Integration with literature-level physical synthesis	Connects production monitoring with excitation mechanisms, transfer paths, and NVH robustness logic
Present review	Manufacturing and assembly variability in EV drivetrains and the resulting NVH scatter	Deviation source $\rightarrow$ excitation $\rightarrow$ transfer $\rightarrow$ radiated noise $\rightarrow$ detectability	—	Provides a focused system-level synthesis linking deviations within nominal tolerance limits, NVH mechanisms, validation depth, and production relevance

4. Structured Framework for Variability-Aware NVH Simulation

The following framework does not introduce fundamentally new modeling principles. Instead, it synthesizes and structures existing approaches reported in the literature into a coherent methodology tailored for variability-aware NVH prediction in electric drivetrains. While many individual elements—such as transmission error analysis, tolerance modeling, or structural-acoustic simulation—are well established, their combined application to predict unit-to-unit NVH variability remains limited.

In this context, the aim of this section is to organize these established practices into a consistent, system-level workflow that reflects production-representative conditions and supports robustness-oriented NVH engineering.

4.1. Explicit Parameterization of Variability Sources

A more robust methodology should therefore begin with the explicit parameterization of the dominant variability sources. Rather than representing manufacturing quality through a single aggregate tolerance measure, the simulation framework should describe the main deviation mechanisms individually. These may include rotor or shaft imbalance, run-out and eccentricity, bearing clearance and preload variation, spline or pilot centering uncertainty, phase indexing during assembly, and temperature-dependent shifts in fits, preload, and lubrication state. Such a formulation is more consistent with real industrial conditions. In practice, the final NVH response is shaped by the combined effect of several small deviations rather than by a single isolated defect.

In practical variability-aware drivetrain simulation, these deviation sources should be parameterized at a finer resolution than is commonly implied by aggregate tolerance values alone. For gear-related variability, this means that pitch-related errors, run-out-like deviations, and microgeometry modifications should, where possible, be introduced at tooth level rather than only as global scalar inputs. Such representations may be derived directly from measurements or generated synthetically using harmonic, random, or user-defined distributions across the teeth. A similarly explicit treatment is beneficial for assembly-related deviations, where eccentricity, angular misalignment, flank-side asymmetry, backlash-related offsets, and centering uncertainty may need to be represented separately instead of being merged into a single generic misalignment term. This more granular parameterization is especially important when explaining sideband generation and ghost-order emergence. It is also required to capture strong unit-to-unit NVH scatter arising from small geometric differences.

A conceptual illustration of this stack-up logic is given in Figure 6, where progressively more severe combinations of deviation sources lead to larger transmission-error fluctuations, richer order content, and higher overall sound pressure level.

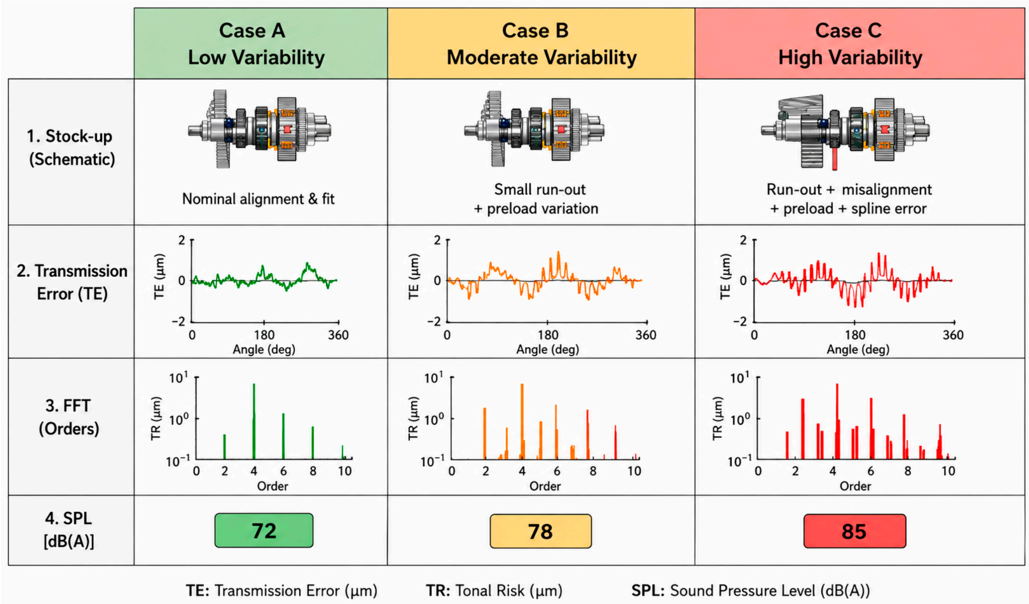

Figure 6. Conceptual effect of assembly stack-up and multi-deviation interaction on transmission error, order content, and overall sound pressure level.

4.2. Hierarchical Simulation Strategy

Once the variability sources are defined, the simulation strategy should follow a hierarchical structure. In the first stage, a computationally efficient reduced-order, linearized, or otherwise simplified model should be used to screen a broad uncertainty space. The purpose of this stage is not to reproduce every local nonlinear contact detail. Instead, it identifies dominant sensitivities, ranks parameter importance, and estimates the spread of key NVH indicators across the tolerance field. This type of first-pass model is especially suitable for design-of-experiments studies, Monte Carlo sampling, or other uncertainty-propagation approaches, which are necessary if the goal is to evaluate robustness rather than only nominal performance. The need for such broader variability sampling is already reflected in the manuscript's discussion of limited current practice and in the cited examples of virtual EOL-type studies and tolerance-based predictive modeling.

In the second stage, the most critical parameter combinations identified in the screening analysis should be re-evaluated using higher-fidelity transient or nonlinear models. This step is important because the most problematic units are not necessarily those with the largest single deviation. Instead, they may arise when several moderate deviations interact unfavorably.

In particular, contact nonlinearities, phase-sensitive superposition, stiffness redistribution, and clearance-closure effects may become decisive only in a refined model. The role of this second stage is therefore to resolve the physical mechanisms behind outlier behavior and to distinguish between broadly influential parameters and those that become important only in specific combinations. This is consistent with the review's conclusion that NVH scatter is often governed by interacting factors rather than isolated deviations.

4.3. Intermediate Excitation Metrics

A further methodological requirement is the use of intermediate excitation metrics between geometry and final noise response. The reviewed evidence repeatedly shows that manufacturing variability acts first on contact conditions, load distribution, and modulation behavior, and only then appears in the final acoustic response. For that reason, the simulation chain should not jump directly from tolerances to sound pressure level alone. Instead, it should include intermediate descriptors such as transmission error, mesh stiffness fluctuation, sideband structure, shaft-order modulation, and local structural vibration. This is particularly important because some deviation types may generate perceptually relevant sidebands or ghost orders even when traditional scalar quality indicators appear acceptable. The manuscript already emphasizes that transmission error is the central linking variable between geometry, excitation, and perceived tonal behavior, and also notes that broader spectral and psychoacoustic characteristics deserve more attention.

For this reason, the intermediate response level should be defined more broadly than transmission error alone. In addition to static or dynamic transmission error, the simulation chain should monitor descriptors such as radial and axial relative position, local misalignment magnitude, the number of teeth simultaneously in contact, contact-pattern evolution, friction-related power loss, and—where lubrication is modeled—oil-film-related quantities. These variables provide a physically interpretable bridge between geometric variability and final acoustic behavior, and they are particularly useful in identifying why some assemblies become outliers even when conventional summary metrics remain within nominal expectations. In robustness-oriented studies, such intermediate outputs can also serve as screening indicators before more computationally expensive structural-acoustic calculations are performed.

4.4. Thermal-State Dependence

Temperature should also be treated as an integral part of the variability problem rather than as a secondary boundary condition. The literature reviewed in the manuscript indicates that thermal expansion, lubricant evolution, and preload shift can change the effective tolerance state of the drivetrain, sometimes causing an assembly to behave differently under cold-start and thermally stabilized conditions. For this reason, variability-aware simulation should include at least a small matrix of representative thermal states, for example cold, nominal, and hot conditions, instead of relying on a single room-temperature prediction. Even where fully coupled thermo-mechanical-acoustic simulation is not feasible, a state-based approach already represents a substantial improvement over purely nominal analysis.

4.5. Structural-Acoustic Response and Perceived Noise

The methodology should then extend from structure-borne response to radiated or perceived noise wherever possible. This is important because two assemblies may show similar levels of mechanical excitation while still differing significantly in radiation efficiency, tonal prominence, or perceptual annoyance. Accordingly, the final assessment should not be based only on internal mechanical metrics, but should connect excitation, transfer path, and acoustic output. The review makes this point explicitly by organizing the literature along the excitation–transfer–radiation chain and by noting that certain deviation types can alter perceived sound quality even when classical transmission error values remain within conventional expectations.

4.6. Integration with Production and Measurement Data

Finally, the reviewed literature strongly suggests that future workflows should connect simulation more directly with production and test data. End-of-line measurements, process information, and component-level inspection data provide an opportunity to anchor simulation models in real manufacturing behavior and to move toward production-relevant prediction rather than nominal design validation alone. In this context, surrogate or hybrid models represent a particularly promising layer above the main simulation workflow. Once a sufficiently broad simulation database has been generated, reduced-order or data-driven predictors can be trained to estimate transmission-error-related risk, tonal-noise indicators, or likely NVH outliers much faster than repeated full-order simulation. The manuscript already identifies this coupling between physics-based and data-driven approaches as an important future direction, especially for robustness-oriented engineering and virtual EOL concepts.

4.7. Summary Framework

Overall, the variability-aware NVH framework synthesized in this review consists of five structured elements derived from the reviewed literature. These are: explicit representation of manufacturing and assembly deviations; hierarchical simulation from broad screening to targeted high-fidelity refinement; evaluation through intermediate excitation metrics and final acoustic outputs; inclusion of thermal and operational state dependence; and systematic connection to production and measurement data. Such an approach is better aligned with the actual industrial challenge. The key question is not whether a single nominal drivetrain is quiet, but whether the full population remains acoustically robust despite unavoidable variability.

In this context, a useful practical distinction can be made between screening-oriented variability models, which are designed to explore wide tolerance spaces efficiently, and refinement-oriented models, which are intended to resolve the local contact and transfer-path mechanisms behind the most critical outlier cases.

It should be emphasized that the value of this framework lies not in introducing new individual modeling techniques, but in integrating them into a consistent variability-aware workflow aligned with industrial NVH challenges.

As an illustrative example, a drivetrain configuration combining moderate run-out, bearing preload variation, and unfavorable phase alignment may exhibit significantly amplified sideband content, even if each individual deviation remains within nominal tolerance limits. This highlights the importance of considering interaction effects rather than isolated parameters in variability-aware NVH prediction.

This interaction logic is summarized qualitatively in Table 5. The example is not intended as a quantitative ranking, but as a compact illustration of how individually acceptable deviations may combine into an unfavorable NVH condition.

Table 5. Qualitative example of interacting variability sources and their expected NVH consequence.

Variability Source	Individual Effect	Interaction Mechanism	Expected NVH Consequence
Moderate gear run-out	Introduces once-per-revolution modulation of the gear-mesh excitation	Generates sidebands around the dominant mesh order	Increased tonal prominence near mesh-related sidebands
Bearing preload variation	Changes support stiffness and shaft constraint conditions	Allows larger shaft motion or local misalignment under load	Increased TE fluctuation and stronger transfer of mesh excitation

Table 5. *Cont.*

Variability Source	Individual Effect	Interaction Mechanism	Expected NVH Consequence
Unfavorable assembly phase alignment	Alters the relative phase of periodic excitation components	Promotes constructive rather than destructive superposition	Amplification of selected orders or sideband components
Combined deviation case	No single deviation necessarily exceeds its nominal tolerance limit	Several moderate deviations interact in the same sensitive operating condition	Possible NVH outlier with elevated tonal noise risk

Table 6 summarizes a general variability-aware simulation framework in which manufacturing and assembly deviations are parameterized explicitly, screened efficiently in reduced-order form, refined through higher-fidelity analysis where needed, and linked to structural, acoustic, and production-oriented response metrics.

Table 6. Proposed variability-aware simulation framework for EV drivetrain NVH prediction.

Variability Source	Generic Simulation Parameterization	Recommended Model Fidelity	Main Response Metrics	Typical Validation Route
Rotor or shaft imbalance	Unbalance magnitude. angular position. and correction plane or planes	Reduced-order or linearized model for screening. high-fidelity transient model for critical combinations	1× order amplitude. shaft-order spectrum. housing vibration. tonal noise increase	Rotor balance data. bench vibration test. order-tracked EOL measurement
Run-out. eccentricity. and shaft tilt	Radial offset. angular tilt. eccentricity length. crossing angle. per-tooth run-out or cumulative pitch error. assembly-induced concentricity error. flank-specific definition where available	Linearized drivetrain model for sensitivity ranking. nonlinear or transient model when contact interaction is important	Transmission error modulation. sidebands around mesh orders. radial and axial relative displacement. misalignment magnitude. housing vibration. ghost-order emergence	CMM or metrology data. shaft alignment checks. component rig tests
Gear microgeometry and waviness	Tooth-level profile. lead. and flank deviation maps. constant-over-teeth or individual-per-tooth definition. harmonic. random. measurement-based. or user-defined distributions. measured flank surfaces where available	Contact-aware reduced-order model for large parameter sweeps. detailed transient contact model for outlier cases	Static or dynamic transmission error. mesh stiffness variation. mesh-force harmonics. sideband level. contact-pattern evolution. number of teeth in contact. friction-related power loss. radiated tonal content	Single-flank TE test. loaded gearbox rig. measured gear inspection data
Bearing clearance. preload. and fit variation	Radial clearance. axial preload. interference or loose fit condition. end-float	Nonlinear structural-dynamic model preferred. reduced-order model acceptable for first-order sensitivity studies	Bearing force variation. misalignment response. housing acceleration. whine level. bearing-related tonal components	Endplay measurement. torque-to-turn. coast-down NVH. bench accelerometer data
Spline or pilot centering variability	Centering offset. backlash. angular misalignment. eccentricity length. crossing angle. competing centering hierarchy between spline and pilot interfaces	Nonlinear transient model preferred. especially where backlash or intermittent contact may occur	Low-order rumble. radial excitation. misalignment-induced transmission error increase. relative radial and axial displacement. local misalignment magnitude. structural resonance triggering	Spline metrology. assembly checks. rig or vehicle boom/rumble validation
Thermal-state-dependent variability	Cold. nominal. and hot state definition. temperature-dependent fits. preload shift. lubricant state. imported thermo-mechanical deformation field where available	State-based simulation matrix first. thermo-mechanically informed high-fidelity model for critical cases	Transmission error shift across temperature states. preload or clearance evolution. order amplification change. temperature-sensitive noise	Conditioned cold/hot tests. thermal rig. repeated EOL or bench measurements at multiple temperatures

Table 6. *Cont.*

Variability Source	Generic Simulation Parameterization	Recommended Model Fidelity	Main Response Metrics	Typical Validation Route
Assembly clocking or phase indexing	Relative angular phase between rotor. gear. shaft. or coupled components. treated as discrete assembly states	Reduced-order model for broad comparison of indexed states. detailed transient model for critical phase interactions	Phase-sensitive order cancelation or amplification. transmission error vector change. housing vibration difference. SPL spread between units	Reassembled unit tests. indexed assembly trials. comparative bench NVH runs
Combined tolerance stack-up	Multi-parameter sampling across imbalance. run-out. clearance. microgeometry. thermal state. and clocking	Uncertainty-propagation workflow using reduced-order or precomputed-contact screening first. followed by refined transient or nonlinear contact simulations for the most critical combinations	Scatter band of transmission error. scatter band of vibration and SPL. outlier probability. robustness ranking	Production scatter data. EOL distributions. selected teardown and re-simulation cases
Structure-borne transfer-path sensitivity	Same excitation case propagated through variable support stiffness. preload. and connection-path conditions	Structural-dynamic transfer-path model. refined local model where necessary	Housing vibration. local path contribution. dominant response nodes. path ranking	Accelerometer array. transfer-path test. comparison of local structural responses
Radiated airborne noise variability	Surface-velocity-based or structurally coupled acoustic radiation analysis for selected variability cases	Acoustic radiation model coupled to structural response	SPL. sound power. directivity. observer-point noise. optionally psychoacoustic indicators	Microphone array. hemi-anechoic or semi-anechoic test. vehicle interior correlation
Surrogate or virtual quality-prediction layer	Reduced-order or data-driven predictor trained on simulation or mixed simulation-test dataset using variability descriptors as inputs	Postprocessing or reduced-order layer built after the main simulation campaign	Fast transmission-error predictor. tonal-noise risk index. virtual pass-fail logic. sensitivity ranking	Hold-out simulation cases. EOL dataset comparison. production anomaly back-check

5. Discussion

The reviewed literature shows that manufacturing and assembly variability is not a secondary refinement issue, but a central determinant of NVH robustness in electric drivetrains. The evidence synthesized in Sections 3.1–3.8 indicates that multiple deviation types can affect the excitation–transfer–radiation chain, but their influence is not equally strong, nor equally well captured by current simulation and validation workflows.

5.1. Most Impactful Deviation Types

The reviewed studies indicate that not all manufacturing and assembly deviations contribute equally to NVH scatter. Among the investigated factors, gear microgeometry deviations—such as profile errors, lead modifications, and waviness—consistently emerge as primary contributors to tonal excitation through their direct influence on transmission error and mesh stiffness variation.

In addition, assembly-related deviations, including shaft misalignment and bearing preload variation, play a critical role in modifying load distribution and excitation transfer paths. These factors do not necessarily generate excitation themselves, but significantly affect how gear-induced forces are transmitted into the structure.

By contrast, certain geometric tolerances or component-level imperfections appear to have a more secondary effect, primarily influencing NVH only when combined with other deviations. This highlights that NVH scatter is typically governed by interacting factors rather than isolated deviations.

Overall, the literature suggests that the most critical contributors are those that directly influence either excitation generation (e.g., microgeometry deviations) or system-level transfer characteristics (e.g., misalignment and preload).

5.2. Are Current Simulation Models Capturing Real Variability?

The reviewed literature indicates that current simulation approaches are highly developed in modeling nominal system behavior, particularly in terms of gear contact analysis, transmission error prediction, and structural dynamics. However, their ability to capture manufacturing- and assembly-induced variability remains limited.

Most simulation workflows rely on nominal geometries or simplified tolerance representations, often neglecting the stochastic nature of real manufacturing deviations. While some studies incorporate parametric variation or Monte Carlo approaches, these are typically restricted to a limited set of parameters and do not fully represent the complexity of real production variability.

A further limitation is that model fidelity strongly affects which variability mechanisms can be explored efficiently and which can be resolved in physical detail. Reduced-order or precomputed-contact approaches are attractive for large parameter sweeps, screening studies, and virtual end-of-line concepts, but they may also restrict the representation of friction, damping, local contact-state evolution, or post hoc geometry changes once the contact dataset has been generated. Conversely, higher-fidelity transient contact formulations provide richer access to local response mechanisms, but their computational cost limits the practical size of the tolerance space that can be explored. As a result, current workflows often face a trade-off between breadth of variability coverage and depth of physical realism, and this trade-off is one reason why nominally correct models may still fail to reproduce real production scatter in a sufficiently robust way.

Furthermore, the integration of measurement-based data—such as gear metrology or assembly condition data—into simulation models is still not widely established. This limits the ability of current tools to reproduce the full variability observed in industrial NVH measurements.

As a result, there is a gap between simulation-based predictions and real-world NVH behavior, particularly in cases where small geometric or assembly deviations lead to significant acoustic differences.

5.3. Underdeveloped Themes

Several important themes remain underrepresented in the current literature on NVH scatter in electric drivetrains.

First, the interaction between multiple deviation sources is not sufficiently explored. Most studies investigate individual factors in isolation, whereas real systems are influenced by combined effects of manufacturing tolerances, assembly conditions, and operational factors.

Second, temperature-dependent variability is only rarely addressed. Despite clear practical relevance, the influence of thermal expansion, lubricant changes, and preload variation on NVH behavior is not systematically studied.

Third, the connection between production data and NVH outcomes remains limited. While some recent works explore data-driven approaches, the integration of end-of-line measurements, process data, and simulation models is still in an early stage.

Finally, higher-frequency and broadband NVH phenomena receive less attention compared to classical gear-mesh tonal components, despite their increasing importance in electric drivetrains.

5.4. Beyond Tonal Mesh Whine: High-Frequency and Perceptual Gaps

While gear-mesh tonal noise remains a dominant focus in the literature, the reviewed studies suggest that NVH behavior in electric drivetrains extends beyond classical tonal excitation.

In particular, higher-frequency content, broadband noise, and modulation effects are becoming increasingly relevant due to the interaction of gear dynamics, electric motor harmonics, and inverter switching phenomena. These effects may not be fully captured by traditional analysis approaches that focus primarily on gear-mesh orders.

Moreover, certain deviation types—such as waviness, run-out, or assembly-induced misalignment—can generate complex spectral features, including sidebands and non-integer order components. These phenomena can significantly influence perceived sound quality, even when classical transmission error metrics remain within acceptable limits.

This indicates that NVH evaluation should not be limited to tonal metrics alone, but should also consider broader spectral characteristics and psychoacoustic aspects.

It should also be clarified that the sound and vibration “limits” discussed in this review do not refer to a single universal threshold applicable to all electric drivetrains. In industrial NVH development, acceptance limits are usually defined internally by OEMs or suppliers and depend on the vehicle segment, measurement position, operating condition, speed range, order definition, and sound-quality target. For this reason, the present review does not define one general limit value for gear whine, shaft-order vibration, or end-of-line NVH metrics.

Where quantitative changes are reported in the reviewed studies, they are interpreted in the context of the corresponding test setup and operating condition. In this manuscript, references to exceedance or acceptability therefore refer to relative changes with respect to study-specific or internally defined criteria, rather than to universal public pass/fail limits. This distinction is particularly important for electric drivetrains, where narrow-band tonal components may become perceptible even when the overall sound pressure level remains moderate.

5.5. Integration of EOL Data with Design and Simulation Tools

The integration of end-of-line (EOL) testing data into NVH analysis represents a promising direction for addressing manufacturing-induced variability.

EOL measurements provide direct information on the acoustic or vibrational behavior of assembled drivetrains and therefore capture the combined effect of manufacturing tolerances and assembly conditions. Several studies indicate that these signals can be correlated with upstream process parameters, enabling root-cause analysis and quality monitoring.

Recent developments in data-driven modeling have further expanded the potential of EOL data, allowing the identification of patterns and relationships that are not easily accessible through conventional simulation approaches.

However, the integration of EOL data with simulation models remains limited. In many cases, measurement data are used for validation or quality control, but not systematically incorporated into predictive modeling frameworks. Bridging this gap could enable more robust and production-relevant NVH prediction methodologies.

5.6. Recommendations for Robustness and Test Design

Based on the reviewed literature, several key recommendations can be formulated for future NVH research and development in electric drivetrains.

First, simulation workflows should increasingly incorporate manufacturing and assembly variability, either through stochastic modeling approaches or through the integration of measurement-based input data.

Second, a closer coupling between simulation and production data is required. The use of EOL measurements and process data in predictive models can improve the representation of real system behavior and enhance model robustness.

Third, NVH evaluation should extend beyond classical transmission error metrics to include broader spectral and psychoacoustic characteristics, particularly in the context of electric drivetrains where tonal perception is critical.

Finally, more attention should be given to multi-domain effects, including thermal influences and the interaction between mechanical and electromagnetic excitation sources.

5.7. Future Directions and Design Outlook

Future research on NVH scatter in electric drivetrains is expected to focus on the integration of physics-based and data-driven approaches. Hybrid modeling frameworks that combine simulation with production and measurement data offer significant potential for improving prediction accuracy and robustness.

In addition, digital twin concepts are likely to play an increasingly important role, enabling continuous feedback between design, manufacturing, and operation. Such approaches could support real-time monitoring and adaptive control of NVH-related characteristics.

Further work is also needed to better understand the combined effects of multiple deviation sources, as well as the influence of thermal and operational conditions on NVH behavior.

Overall, advancing NVH prediction in electric drivetrains will require a more integrated and multidisciplinary approach, combining mechanical design, manufacturing engineering, data science, and acoustics.

6. Conclusions

This review has shown that manufacturing and assembly variability is a major source of NVH scatter in electric drivetrains, and that its importance is amplified by the absence of combustion-engine masking. The reviewed literature consistently indicates that deviations such as rotor imbalance, gear run-out, indexing error, bearing clearance variation, shaft misalignment, and spline coupling imperfections can alter the excitation–transfer–radiation chain and lead to perceptible tonal differences between nominally identical units.

Among the reviewed deviation types, gear-related errors that directly increase transmission error or generate sidebands appear especially influential. At the same time, assembly-related effects such as preload variation, run-out stacking, and phase indexing can significantly modify the final NVH outcome even when individual components remain within tolerance. The evidence further suggests that industrial NVH control is shifting from nominal design optimization toward robustness-oriented engineering, supported by end-of-line NVH testing, order-based diagnostics, AI-assisted anomaly detection, virtual EOL concepts, and predictive tolerance analysis.

Beyond summarizing individual mechanisms, this review synthesizes the available evidence into a structured framework for variability-aware NVH simulation in electric drivetrains. The framework organizes existing practices around five main elements: explicit representation of dominant deviation sources; hierarchical simulation from broad variability screening to targeted high-fidelity refinement; evaluation through intermediate excitation metrics and final acoustic outputs; inclusion of thermal and operational state dependence; and systematic connection to production and measurement data. In this way, the contribution of the paper is not the introduction of a new individual modeling technique, but the integration of established concepts into a coherent workflow for robustness-oriented NVH engineering.

Important research gaps remain in multi-error interaction modeling, temperature-dependent NVH behavior, spline coupling dynamics, and the integration of production data into predictive simulation environments. Addressing these gaps will support quieter and more robust EV drivetrain designs and help move the field from nominal NVH assessment toward production-representative prediction of real acoustic scatter.

Overall, manufacturing and assembly variability should be treated not as a secondary disturbance, but as a quantifiable and manageable dimension of drivetrain NVH engineering. By combining precision engineering with advanced simulation, measurement-informed modeling, and smart testing, the industry can move closer to consistently quiet electric drives at population level rather than relying on nominal design alone.

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Abbreviations

The following abbreviations are used in this manuscript:

NVH	Noise, vibration, and harshness
EV	Electric vehicle
EDU	Electric drive unit
EOL	End-of-line
TE	Transmission error
TIR	Total indicator run-out
OEM	Original equipment manufacturer
PMSM	Permanent magnet synchronous motor
ICE	Internal combustion engine
CMM	Coordinate measuring machine
MBD	Multibody dynamics
FEA	Finite element analysis
SPL	Sound pressure level
GMF	Gear mesh frequency
TRI	Tonal Risk Index
QC	Quality control

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