

From Manufacturing Measurements to Variability-Aware NVH Simulation of Electric-Vehicle Gearboxes: A Simulation-Ready Parameter Framework

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Detailed simulation-ready parameter tables and supplementary workflow figures

The tables preserve the detailed engineering data-request content of the original manuscript. Priority labels are conditional and must be interpreted with the readiness rules and limitations in the main article.

Table S1. Gear geometry, microgeometry, and manufacturing-deviation inputs for simulation-ready EV gearbox NVH models.

Parameter	Typical Unit	Typical Source	Main NVH Effect	Numerical Representation	Priority
Tooth number	–	CAD / drawing	Mesh-order definition	Gear pair definition	Baseline
Module	mm	CAD / drawing	Contact stiffness and geometry	Gear pair definition	Baseline
Pressure angle	deg	CAD / drawing	Force direction and tooth stiffness	Gear pair definition	Baseline
Helix angle	deg	CAD / drawing	Overlap ratio and axial force	Gear pair definition	Baseline
Face width	mm	CAD / drawing	Load distribution	Gear pair definition	Baseline
Tip relief	μm	Design / coordinate measuring machine (CMM)-based topography mapping	Loaded TE reduction	Profile modification curve	Baseline
Lead crowning	μm	Design / CMM	Misalignment robustness	Lead modification curve	Baseline
Profile deviation	μm	Gear inspection	TE variation	Flank surface offset	Baseline
Lead deviation	μm	Gear inspection	Face-load variation	Flank line correction	Baseline

Parameter	Typical Unit	Typical Source	Main NVH Effect	Numerical Representation	Priority
Pitch error	μm / arcsec	Gear inspection	Mesh modulation and side-bands	Tooth-indexed error vector	Recommended
Cumulative pitch error	μm / arcsec	Gear inspection	Low-order modulation	Circumferential error vector	Recommended
Runout / eccentricity	μm	Gear inspection	Center-distance modulation	Eccentricity vector	Recommended
Tooth-to-tooth variation	μm	Tooth-wise inspection	Local excitation variation	Tooth-specific maps	Advanced
Surface roughness	Ra, Rz	Surface measurement	Contact and tribological effects	Roughness descriptor	Recommended
Flank waviness	μm, wavelength	Topography measurement	Ghost tones / non-classical tones	Surface waviness map	Advanced

Table S2. Flank-waviness and surface-topography inputs for simulation-ready EV gearbox NVH models.

Parameter	Typical Source	Main NVH Effect	Numerical Representation	Priority
Waviness amplitude	Flank topography measurement	Tonal excitation strength	Periodic surface deviation	Recommended
Waviness wavelength	Surface measurement / process data	Order location and modulation	Spatial harmonic descriptor	Recommended
Waviness phase	Tooth-wise surface map	Tooth-to-tooth modulation	Phase-defined surface excitation	Advanced
Tooth-to-tooth topography variation	High-density flank measurement	Sidebands / tonal scatter	Tooth-specific flank maps	Advanced
Grinding signature	Process and surface data	Ghost-order risk	Process-related waviness pattern	Advanced
Honing topography	Process and surface data	Surface-related tonal effects	Surface descriptor or map	Advanced
Surface roughness	Surface profilometry	Contact and tribology influence	Statistical roughness descriptor	Recommended
Full flank topography	Optical / CMM scanning	Detailed excitation representation	Direct flank map	Advanced

Table S3. Assembly-alignment and mounting inputs for simulation-ready EV gearbox NVH models.

Assembly Parameter	Typical Source	Main NVH Effect	Numerical Representation	Priority
Center distance error	Housing / assembly measurement	Backlash and contact-ratio variation	Shaft-axis offset	Baseline
Angular misalignment	Assembly or bore measurement	Face-width load redistribution	Shaft-axis rotation	Baseline
Parallel offset	Assembly measurement	Contact pattern shift	Translational offset	Recommended
Skew error	Housing / shaft measurement	Contact-line distortion	Shaft-axis transformation	Recommended
Axial offset	Assembly datum	Face-width contact shift	Axial coordinate offset	Recommended
Gear mounting tilt	Shaft-gear fit measurement	Effective lead error	Gear local-coordinate rotation	Advanced
Backlash	Gear / assembly inspection	Rattle and impact excitation	Nonlinear dead band	Baseline
Temperature-dependent backlash	back- Thermal test or estimate	Warm-state contact variation	Backlash-temperature table	Recommended
Bearing seat position	CMM / housing inspection	Shaft support shift	Bearing coordinate offset	Recommended
Bore coaxiality	CMM / housing inspection	Support misalignment	Bearing-axis correction	Recommended
Shim thickness	Assembly record	Shaft position and preload	Axial offset / preload input	Recommended
Endplay	Assembly measurement	Axial support variation	Axial clearance parameter	Recommended

Table S4a. Bearing-model fidelity levels and supported applications.

Modeling Level	Typical Input Data	Main Advantage	Main Limitation	Typical Use
Scalar radial stiffness	Radial stiffness	Fast and simple	No axial or tilting behavior	Early concept model
Directional stiffness	Radial, axial, tilting stiffness	Better support realism	Requires more data	System-level NVH
Stiffness-damping support	Directional stiffness and damping	Improved dynamic response	Damping uncertainty	Correlation studies
Nonlinear bearing support	Clearance, preload, load-dependent stiffness	Captures state dependence	Higher data demand	Detailed troubleshooting
6 x 6 matrix support	Full stiffness / damping matrix	Best compact transfer-path description	Supplier/test data often needed	High-fidelity MBD/FEM

Modeling Level	Typical Input Data	Main Advantage	Main Limitation	Typical Use
Full rolling-element model	Detailed bearing geometry	Local bearing dynamics	High effort and cost	Research-level analysis

Table S4b. Detailed bearing and support-state data package for simulation-ready EV gearbox NVH models.

Parameter	Priority	Typical Source	Main NVH Role	Numerical Representation
Bearing type	Baseline	Bearing specification	Defines support family	Bearing model selection
Inner diameter, d	Baseline	Catalogue / supplier	Basic geometry	Geometric parameter
Outer diameter, D	Baseline	Catalogue / supplier	Basic geometry	Geometric parameter
Width, B	Baseline	Catalogue / supplier	Basic geometry	Geometric parameter
Inner/outer ring connection	Baseline	MBD/FEM setup / assembly data	Defines shaft-housing transfer path	Shaft/housing marker or node connection
Local coordinate frame / orientation	Baseline	MBD/FEM setup	Defines radial, axial, and tilting directions	Local bearing coordinate frame
Fixed/floating/preloaded arrangement	Baseline	Assembly design / layout	Defines axial support and pre-load behavior	Support arrangement definition
Internal clearance	Baseline	Supplier / assembly data	Support state	Clearance parameter
Preload	Baseline	Assembly data	Shaft guidance and stiffness	Preload input
Operating load, Fr and Fa	Baseline	MBD load case / test	Load-dependent stiffness and contact state	Radial and axial bearing load input
Radial stiffness	Baseline	Supplier / calculation / test	Main force transfer	Radial support stiffness
Axial stiffness	Recommended	Supplier / calculation / test	Axial-force transfer	Axial stiffness
Tilting stiffness	Recommended	Supplier / calculation / test	Shaft alignment and bending response	Rotational stiffness
Damping	Recommended	Test / estimate	Resonance amplitude	Damping coefficient
Contact angle	Recommended	Supplier	Radial-axial coupling	Bearing parameter
Rolling-element number	Recommended	Supplier	Internal kinematics	Bearing model input
Rolling-element diameter or length	Recommended	Supplier	Contact stiffness	Bearing model input

Parameter	Priority	Typical Source	Main NVH Role	Numerical Representation
Effective assembly stiffness	Recommended	Assembly / housing-shaft model	Actual preload and interface compliance	Surrounding-structure stiffness
Shaft/housing fits	Recommended	Drawing / assembly data	Clearance reduction and ring deformation	Fit / interference input
Full connection-point coordinates	Recommended	MBD/FEM setup	Correct support location and force application	x, y, z marker or node coordinates
Operating temperature	Recommended	Test / thermal model	State-dependent stiffness	Temperature-dependent input
Lubricant state	Recommended	Oil specification	Friction and damping	Lubrication parameter
Load-dependent stiffness	Advanced	Supplier / model	Nonlinear response	Lookup table
Temperature-dependent stiffness	Advanced	Supplier / model	Warm-state response	Lookup table
Raceway / rolling-element form error	Advanced	Inspection / supplier	Bearing-origin periodic excitation	Form-error descriptor or excitation input
Nonlinear force-displacement curves	Advanced	Supplier / bearing model	Detailed support behavior	Nonlinear bearing law
6 x 6 stiffness matrix	Advanced	Supplier / test / calculation	Compact transfer-path model	Matrix input
Detailed rolling-element geometry	Advanced	Supplier / bearing model	Local contact behavior	Detailed internal geometry
Lubrication-film data	Advanced	Tribology model / test	Friction and damping mechanism	Lubrication-film model

Table S5. Shaft, rotor, interface, and electromechanical inputs for simulation-ready EV gearbox NVH models.

Parameter	Typical Source	Main NVH Effect	Numerical Representation	Priority
Shaft geometry	CAD	Bending and torsional compliance	Beam or flexible-body model	Baseline
Shaft mass and inertia	CAD / measurement	Dynamic response	Rigid or flexible body properties	Baseline
Shaft support locations	CAD / assembly	Bearing reaction forces	Bearing coordinate definition	Baseline

Parameter	Typical Source	Main NVH Effect	Numerical Representation	Priority
Shaft flexibility	FEM / reduced model	Mesh alignment and force transfer	Modal or beam representation	Recommended
Imbalance	Balancing data	1× shaft-order excitation	Rotating force vector	Recommended
Runout	Inspection data	Mesh-force modulation	Geometric eccentricity	Recommended
Gear eccentricity	Gear measurement	Sidebands and center-distance variation	Eccentricity vector	Recommended
Rotor offset	Motor inspection / EM model	Air-gap force variation	Static or dynamic eccentricity	Recommended in e-drives
Torque ripple	Motor model / test	Torsional excitation	Harmonic torque input	Recommended in e-drives
Electromagnetic tooth forces	Motor FE model	Motor-order excitation	Harmonic force map	Advanced
Spline backlash	Interface measurement	Rattle and transient impacts	Nonlinear clearance	Recommended
Coupling stiffness	Supplier / test	Torsional transfer	Stiffness-damping element	Recommended

Table S6. Housing, joint, and structural-transfer inputs for simulation-ready EV gearbox NVH models.

Parameter	Typical Source	Main Structural Effect	Main NVH Effect	Numerical Representation	Priority
Housing geometry	CAD	Defines structural layout	Modal behavior	FE geometry	Baseline
Material properties	Specification / test	Elastic response	Mode frequencies	FE material model	Baseline
Wall thickness	CAD / measurement	Local mass and stiffness	Panel vibration	Shell or solid geometry	Baseline
Wall-thickness variation	CT / measurement	Local stiffness scatter	Unit-to-unit NVH scatter	Thickness field	Recommended
Bearing seat position	CMM / CAD	Support location	Force-path definition	Bearing interface coordinates	Baseline
Bearing seat stiffness	FE / test	Local compliance	Bearing-force transfer	Local stiffness representation	Recommended
Rib geometry	CAD	Local reinforcement	Mode-shape modification	FE geometry	Recommended
Cover and flange geometry	CAD	Interface stiffness	Local radiation behavior	FE geometry / contact	Recommended
Bolted-joint stiffness	Test / estimate	Interface dynamics	Transfer-path modification	Joint elements	Recommended
Bolted-joint damping	Test / estimate	Energy dissipation	Resonance amplitude	Damping representation	Advanced

Parameter	Typical Source	Main Structural Effect	Main NVH Effect	Numerical Representation	Priority
Structural damping	experimental modal analysis (EMA) / estimate	Response amplitude	Radiated noise level	Modal damping / loss factor	Recommended
Mount stiffness	Test / supplier	Boundary condition	System response	Spring-damper support	Recommended
Bearing-seat FRFs	Test	Interface dynamics	Model validation	FRF target	Advanced

Table S7. Vibroacoustic inputs, outputs, and validation quantities for EV gearbox NVH models.

Parameter	Typical Source	Main Role	Numerical Representation	Priority
Surface velocity	FEM / measurement	Main structural acoustic input	Velocity field	Baseline
Surface acceleration	FEM / accelerometers	Diagnostic response indicator	Acceleration field	Recommended
Structural mode shapes	FEM / modal test	Radiation pattern influence	Modal basis	Recommended
Radiation efficiency	Acoustic model / estimate	Vibration-to-sound conversion	Radiation coefficient	Recommended
Acoustic Transfer Function	Test / acoustic simulation	Receiver sensitivity	Transfer function / matrix	Recommended
ERP	Structural-acoustic processing	post-pro- Panel ranking	ERP metric	Recommended
Acoustic intensity	Measurement	Source localization	Intensity map	Recommended
Sound power level	Measurement / simulation	Global acoustic output	Acoustic metric	Baseline
Microphone positions	Test setup	Receiver definition	Acoustic receiver set	Baseline
Acoustic boundary conditions	Test / vehicle environment	Sound-field definition	Acoustic model input	Recommended
finite element method–boundary element method (FEM–BEM) coupling	Structural-acoustic model	Radiation prediction	Coupled simulation	Advanced

Table S8. Operating, thermal, lubrication, and degradation inputs for simulation-ready EV gearbox NVH models.

Parameter	Typical Source	Main NVH Effect	Numerical Representation	Priority
Rotational speed	Test / duty cycle	Order frequency definition	Speed profile or map	Baseline
Torque	Test / duty cycle	Loaded TE and bearing reactions	Torque profile or map	Baseline
Drive / coast state	Control logic / test condition	Flank change and rattle risk	Signed torque state	Baseline

Parameter	Typical Source	Main NVH Effect	Numerical Representation	Priority
Acceleration / deceleration	Drive cycle	Transient excitation	Time-dependent operating input	Recommended
Oil temperature	Test / thermal model	Viscosity, preload, backlash	Temperature state	Recommended
Lubricant viscosity	Oil specification	Contact and damping behavior	Temperature-dependent property	Recommended
Oil level	Test / specification	Lubrication regime	Boundary condition	Recommended
Running-in state	Test history	Contact surface evolution	Discrete condition state	Recommended
Flank wear	Inspection / model	TE and contact change	Updated flank geometry	Advanced
Backlash growth	Inspection / estimate	Rattle and impact excitation	Updated clearance	Recommended
Bearing clearance growth	Inspection / estimate	Support stiffness change	Updated bearing parameter	Recommended
Surface damage	Inspection	Local excitation and roughness	Damage-state variable	Advanced
End-of-life condition	Durability test	Combined degradation effects	Scenario definition	Advanced

Table S9. Numerical model-form fidelity, additional data requirements, and verification outputs.

Subsystem	Reduced-order representation	Intermediate representation	High-fidelity representation	Additional inputs required	Main verification outputs
Gear contact	Prescribed TE, mesh stiffness or force map	Rigid nonlinear flank contact with backlash and misalignment	Flexible-tooth or fully flexible gear contact	Flank geometry, microgeometry, deviations, FE modal data	TE, mesh force, contact pattern, pressure
Bearing support	Ideal joint or scalar stiffness	Directional or six-component nonlinear support	Rolling-element and raceway compliance-based model	Clearance, preload, contact angle, rolling-element geometry, fits and temperature	Bearing forces, moments, displacement and tangent stiffness
Shaft and gear body	Rigid body	Beam or reduced flexible body	Modal FE flexible body	Interface coordinates, material data, modes and damping	Deflection, misalignment and modal participation
Manufacturing data transfer	Manual scalar input	Tabulated deviation or parameter import	Measured flank/topography and standardized CAE-data exchange	Units, coordinate systems, conventions, part identity and version metadata	Data traceability and reproducibility

Table S10. Full mapping of physical parameters to LTCA, MBD, FEM, vibroacoustic, and data-driven domains.

Parameter Group	LTCA / Contact Analysis	MBD	FEM	Vibroacoustic	Data-Driven Use
Gear macrogeometry	Direct gear definition	Gear pair definition	Indirect	Indirect	Geometry features
Gear microgeometry	Flank modification	Mesh excitation influence	Indirect	Indirect	Relief and crowning features
Profile and lead deviations	Surface deviation field	Equivalent TE / mesh excitation	Indirect	Indirect	Deviation statistics
Pitch error	Tooth-indexed pitch vector	Modulated excitation	Indirect	Indirect	Tooth-index features
Runout / eccentricity	Center-distance variation	Eccentricity excitation	Bearing force variation	Indirect	Runout amplitude and phase
Flank waviness	Surface map or harmonic descriptor	Equivalent excitation	Indirect	Indirect	Waviness descriptors
Assembly misalignment	Axis offset in contact model	Shaft-axis transformation	Support coordinate shift	Indirect	Alignment features
Backlash	Clearance in contact model	Nonlinear dead band	Indirect	Indirect	Clearance value / state
Bearing preload / clearance	Support condition if coupled	Preload-dependent stiffness	Interface condition	Indirect	Bearing state features
Bearing stiffness	Support stiffness if coupled	Bearing support model	Interface impedance	Indirect	Stiffness features
Shaft flexibility	Mesh alignment influence	Flexible shafts	Optional reduced body	Indirect	Shaft dynamic descriptors
Imbalance	Not usually direct	Rotating force	Interface force effect	Indirect	Imbalance magnitude / phase
Torque ripple	Load modulation	Harmonic torque input	Interface load effect	Indirect	Harmonic order features
Housing geometry	Not direct	Reduced flexible body if used	Structural FE geometry	Radiation surface	Modal features
Wall thickness	Not direct	Indirect	Thickness field	Radiation influence	Thickness descriptors
Structural damping	Not direct	Optional	Damping model	Affects radiation response	Identified damping features
Surface velocity	Not direct	Not direct	Response output	Main acoustic input	Vibroacoustic target
Acoustic transfer function	Not direct	Not direct	Optional post-processing	Acoustic sensitivity	Contribution feature

Parameter Group	LTCA / Contact Analysis	MBD	FEM	Vibroacoustic	Data-Driven Use
Speed and torque	Load condition	Operating profile	Load case definition	Receiver condition	Operating features
Degradation state	Updated flank geometry	Updated clearance / support	Updated stiffness / damping	Updated response	State label

Bearing data as NVH transfer-path inputs



Bearing data influence how gear-mesh forces enter the housing.



A detailed gear-contact model with arbitrary bearing supports may be insufficient for system-level NVH correlation.

Figure S1. Recommended bearing data package and transfer-path inputs for detailed gearbox NVH modeling.

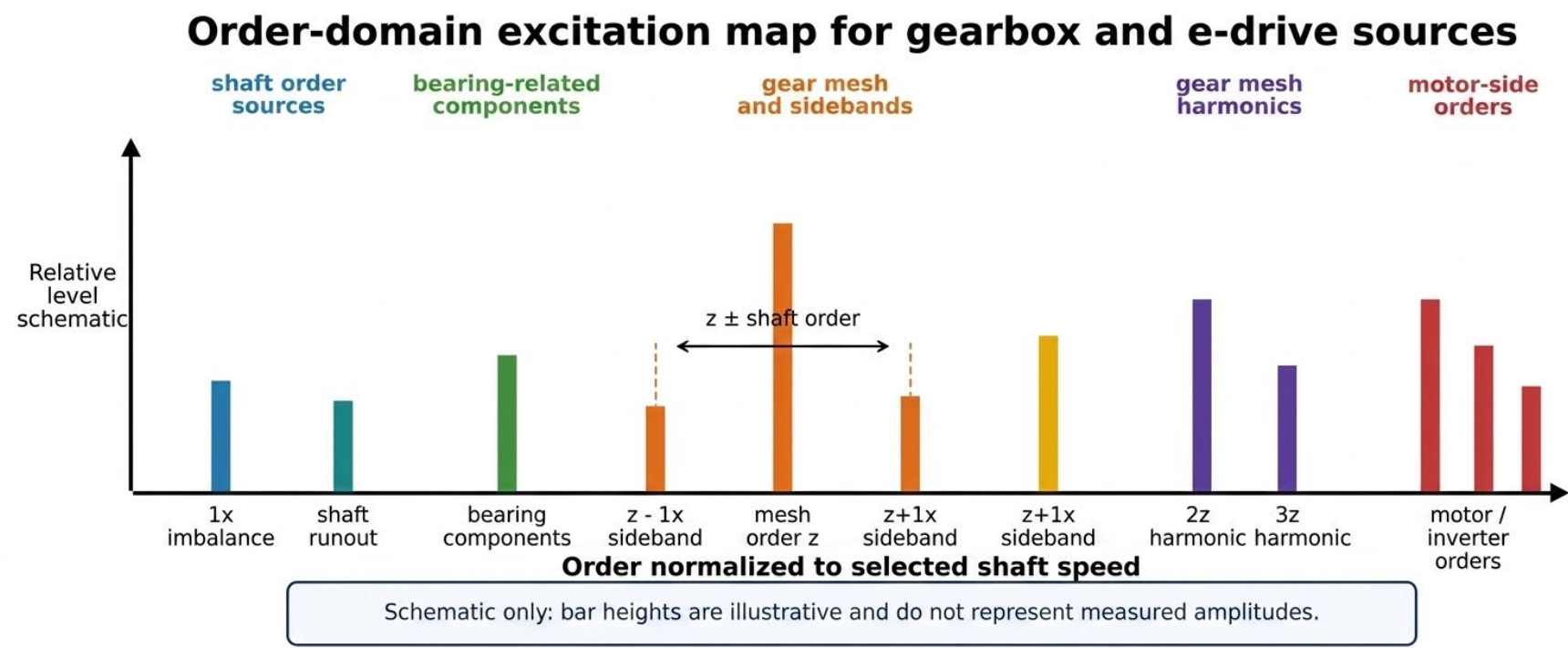


Figure S2. Order-domain map of gear, shaft, bearing, and electromechanical excitation families.

Table S11. Abbreviations used in the main manuscript and supplementary material.

2D	Two-dimensional
3D	Three-dimensional
ATF	Acoustic transfer function
BEM	Boundary element method
CAD	Computer-aided design
CAE	Computer-aided engineering

2D	Two-dimensional
CMM	Coordinate measuring machine
CT	Computed tomography
EMA	Experimental modal analysis
ERP	Equivalent radiated power
FE	Finite element
FEM	Finite element method
FRF	Frequency response function
ISO	International Organization for Standardization
LTCA	Loaded tooth contact analysis
MBD	Multibody dynamics
NVH	Noise, vibration, and harshness
PMSM	Permanent magnet synchronous motor
SPL	Sound pressure level
TE	Transmission error