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Article

Integrated Durability and Parametric Validation of a Linear Ball-Screw-Driven Gear Shifter

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Abstract

Electromechanical gear-shifting systems require low friction and repeatable motion while retaining force, speed, stroke, and response after long-duration cyclic service. This study integrates baseline and post-durability parametric measurements with teardown observations for a two-motion Gear Shifter intended for medium- and heavy-duty transmission applications. The anonymized dataset contains rail-selection and gear-engagement durability groups exposed to as many as 8.4 million shifts. Shift-finger force, no-load velocity, motor/shifter breakaway current, half-travel, and half-shift time were evaluated using the aggregate means, percentage changes, observation counts, dispersion measures, and ranges available in the source dataset. Aggregate post-versus-pre mean changes were calculated descriptively; inferential paired testing was not attempted because raw paired observations were unavailable. Retention was assessed against baseline using the direction of adverse change for each response; the largest adverse aggregate mean change was 1.7% (half-travel), and no adverse change occurred in breakaway current or half-shift time. Rail-selection force increased after both durability exposures, whereas gear-engagement force was nearly unchanged in the aggregate; however, its dispersion increased by 43%, and a descriptive lower-tail indicator (mean − 2SD) fell by 24%, showing that mean-only retention can conceal degradation in weaker units. Velocity remained close to baseline, half-travel decreased by 0.3–1.7%, half-shift time decreased by 1.0–4.6%, and breakaway-current means decreased by 3.0–8.5%. Eight of twelve development motors failed during gear-engagement durability, and most corresponding post-test measurements used replacement motors; the results therefore separate original-motor survival, replacement-motor system function, and mechanical-actuator retention. Teardown evidence included thrust-washer pitting/scoring and ball-screw pitting, reported qualitatively. The contribution is a transferable evidence-integration and reporting procedure for actuator durability validation, not a new durability or reliability model.

Keywords: Gear Shifter; electromechanical actuator; automated manual transmission; durability validation; ball screw; breakaway current; hysteresis; failure analysis

1. Introduction

Automated manual transmissions and non-synchronizer transmission variants require gear-shift actuators that can convert electrical command signals into repeatable rail-selection and gear-engagement motion under nonlinear friction, load disturbance, backlash, hysteresis, and uncertain operating conditions [1–5]. In such systems, the actuator is not merely an auxiliary device; it is a governing element in shift quality, response time, mechanical engagement repeatability, and long-term reliability. Recent direct-drive and dual-linear-actuator studies show that removing intermediate mechanical stages can reduce hysteresis and improve dynamic response, but the actuator

still must satisfy force, displacement, timing, and disturbance-rejection requirements during the complete shift event [3,4]. In this context, the Gear Shifter examined in the present work is best understood as a durability-critical electromechanical system rather than as a simple motion converter: its validation must address not only whether the commanded shift can be completed, but whether the output functions remain stable after long-cycle exposure.

The transition from hydraulically assisted or mechanically linked shift systems toward compact electromechanical actuation increases the importance of measurable validation evidence. Electromechanical architectures offer packaging flexibility, electronic controllability, and the potential for lower parasitic losses, but these advantages are useful only when the actuator can maintain functional capability despite friction changes, temperature exposure, vibration, repeated cycling, lubrication redistribution, and component wear. A gear-shift actuator must therefore be assessed at several levels: the controller must generate appropriate command trajectories, the motor must deliver adequate torque or force margin, the motion-conversion mechanism must preserve displacement and stiffness, and the final shift-finger output must remain capable of meeting the transmission interface requirement. A validation study that reports only a pass/fail outcome can hide important distinctions between these levels.

Durability evaluation becomes more complex when the mechanism contains ball-screw elements and loaded thrust interfaces. Ball screws can provide efficient and repeatable conversion of rotary motion into linear displacement, yet their performance depends on contact condition, preload, surface integrity, lubrication film behavior, alignment, and support stiffness. Pitting, scoring, and preload change may develop gradually and may not immediately prevent the actuator from completing a shift. As a result, retained actuator-level function and component-level distress can coexist. This coexistence is central to the present manuscript because it shows why functional measurements and teardown evidence should be interpreted together rather than treated as competing forms of evidence.

Control-oriented gear-shift research has emphasized accurate position tracking when parameters are uncertain and external disturbances are present [1,2,5,17–19]. Hardware-in-the-loop and vehicle-actuation studies further show the value of planned sleeve trajectories, disturbance-aware control, and active synchronization strategies [2,17–19]. These contributions are essential for actuator control design, but they do not fully answer a durability-release question: whether the same mechanism retains output force, velocity, travel, current demand, and response time after millions of repeated functional cycles. For industrial validation, the release argument must therefore connect controller-level performance, mechanical conversion efficiency, test repeatability, and inspection evidence.

A further challenge is that industrial validation datasets often contain aggregate statistics rather than complete time histories. Mean force, velocity, current, travel, and timing values are useful for describing retention, but they do not by themselves establish specimen-level causality, paired degradation rate, or statistically independent durability response. Changes in measured current may be influenced by motor replacement, run-in, lubricant redistribution, preload change, or test-stand behavior. Likewise, modest changes in travel or timing may reflect measurement resolution, conditioning sequence, or actual mechanical change. For this reason, the present paper deliberately frames the dataset as a descriptive validation study rather than as a controlled tribological experiment.

The study also has practical engineering significance. Release decisions for electromechanical shifting devices rarely depend on a single metric. A design can satisfy measured output-force and timing requirements while still presenting motor durability concerns, measurement-process uncertainty, or early evidence of surface distress. Conversely, a component may show localized pitting without immediate loss of system-level function. A useful validation argument must therefore separate what the data strongly support from what they cannot prove. In the present case, the strongest supported claim is that the measured rail-selection and gear-engagement functions were

retained at the aggregate level after severe durability exposure. The weaker and unresolved claims concern causal explanations for current reduction, the long-term implications of pitting/scoring, and the durability of the original development motor population.

The durability problem is especially important for ball-screw-driven actuation because pitting, preload degradation, and raceway distress can develop progressively and may be observed directly or indirectly through condition indicators [10–16,25–31]. Motor-current-based diagnostics also demonstrate that current signals can contain useful information about ball-screw condition when direct vibration measurement is impractical [9,17]. However, current, velocity, and force signatures remain system-level indicators; they are affected by preload, lubrication state, motor replacement, run-in, external load, and test-stand behavior. The industrial validation dataset examined here therefore addresses a practical evidence-integration gap: it combines long-duration function-specific durability, pre/post parametric summaries, replacement history, omitted observations, and teardown evidence, while explicitly avoiding unsupported causal claims.

Accordingly, the objective of this paper is to convert an anonymized durability-validation dataset into a coherent technical argument for electromechanical Gear Shifter assessment. The paper first reviews literature on gear-shift actuator control, friction/current interpretation, ball-screw degradation, and durability validation. It then defines the system terminology, measurement structure, exclusions, confounders, and the baseline-referenced basis used for retention claims before presenting aggregate pre/post results. The discussion interprets the results at three separate system boundaries—original-motor survival, replacement-motor system function, and mechanical-actuator retention—and states explicitly which quantitative conclusions the aggregate data can and cannot support. This structure is intended to support a bounded publication claim: the dataset provides descriptive evidence of baseline-referenced functional retention, but it does not independently prove original motor durability, specification compliance, reliability, or a causal wear mechanism.

The introduction establishes the need for an integrated interpretation of actuator performance and physical distress. The following review narrows that problem by positioning the study among four related bodies of work: gear-shift actuator control, friction and current interpretation, ball-screw degradation, and durability-validation methodology.

2. Literature Review and Research Gap

2.1. Gear-shift actuation and performance variables

Gear-shifting research commonly represents the actuator as an electromechanical plant subject to nonlinearity, parameter uncertainty, and external disturbance [1–5,18,19]. For non-synchronizer automated mechanical transmissions, precise actuator tracking is needed because sleeve trajectory and active synchronization directly affect shifting quality [2,18,19]. Direct-drive or dual-linear-actuator configurations reduce intermediate mechanisms and can improve dynamic capability, but they also make displacement accuracy, force fluctuation, and stable endpoint engagement central validation variables [3,4]. Electromagnetic and linear-actuator studies therefore make shift force, trajectory tracking, actuator velocity, and response time technically relevant measures rather than secondary descriptive quantities [4]. At the gear-selector level, Zhong et al. [43] evaluated a DC-motor-driven gear selector for automated manual transmissions, combining a mathematical model of the shifting process, scheme selection, linear-quadratic-regulator position control, and on-vehicle calibration testing; their work shows that a selector concept must be validated for shifting stability under real operating conditions and not only through actuator-level control performance. The present manuscript follows that logic by treating force, no-load velocity, travel, current, and half-shift time as complementary indicators of functional retention after durability exposure. The

relationships among command generation, motor actuation, ball-screw conversion, shift-finger output, and shift-quality objectives are summarized in Figure 1.

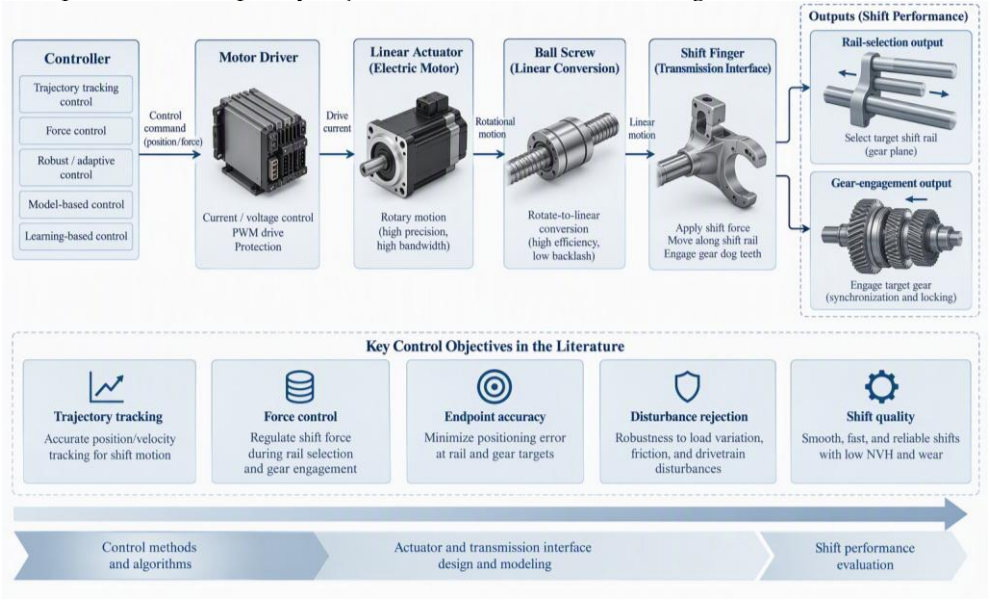


Figure 1. Literature map of gear-shift actuator-control research linking command generation, motor actuation, ball-screw conversion, shift-finger output, and shift-quality objectives.

2.2. Friction, current, and run-in

Breakaway current is useful as a system-level friction proxy because motor-current models of electromechanical actuator ball screws show that torque-producing current can respond to simulated healthy, degrading, and faulty friction states [9,17]. Higher-fidelity work further shows that peak starting-current features and transient current behavior can contain information about dynamic ball-screw friction, although classification accuracy is limited when load disturbance and modelling uncertainty are present [17,21–24]. This literature supports using current as a diagnostic indicator, but it also cautions against treating current as a direct friction coefficient [6,8,9,17,35,36]. In the present dataset, a post-test current decrease may reflect running-in, lubrication redistribution, changed motor characteristics, reduced preload, measurement conditioning, or combinations of these effects; therefore, it is interpreted as an actuator-system response rather than proof of reduced wear. The factors influencing breakaway current in this interpretation are shown in Figure 2.

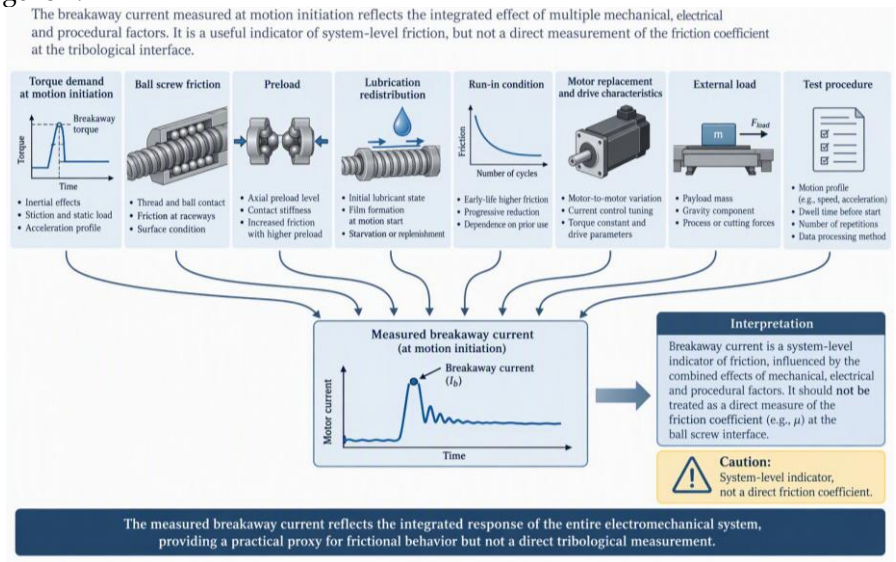


Figure 2. Breakaway current interpreted as a system-level friction proxy influenced by torque demand, ball-screw friction, preload, lubrication, run-in, motor characteristics, external load, and test procedure.

2.3. Ball-screw wear and pitting

Ball-screw feed systems rely on preload to reduce backlash and maintain dynamic rigidity, but preload loss can be detected through vibration features around ball-pass-frequency content [7,14–16,26,27,31]. Sensorless and model-based approaches have also estimated preload state from machine-control data, demonstrating that preload degradation is both functionally important and diagnostically observable [15,16,26,27,30,31]. Dynamic signal analysis and order-tracking methods further show that sideband energy and harmonic features can discriminate preload deterioration and backlash conditions during operation [14–16,26]. Digital-twin approaches extend this direction by linking physical models and monitoring data for ball-screw condition assessment [31]. These studies support treating the observed pitting/scoring and possible preload change as credible degradation evidence, while also showing why specimen-level time histories are needed before assigning aggregate actuator performance shifts to a specific physical mechanism. The links between these degradation modes and measurable condition indicators are mapped in Figure 3.

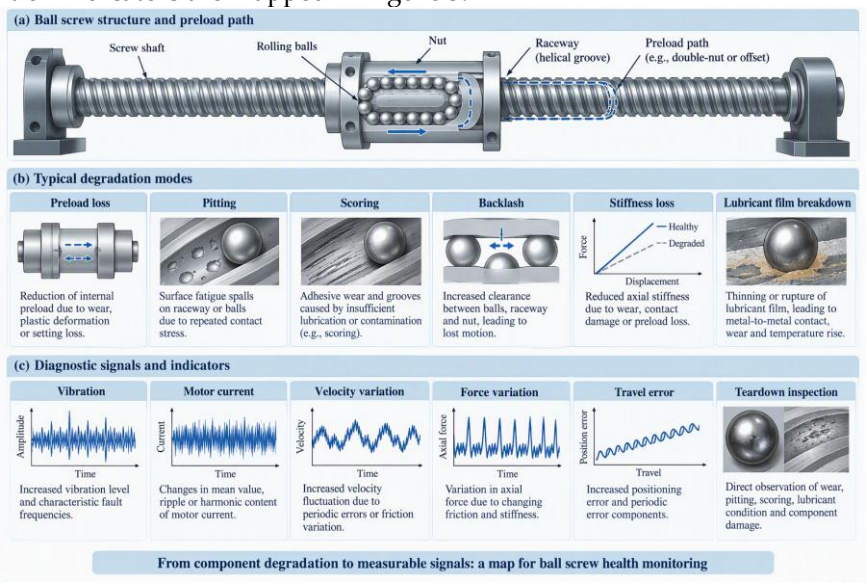


Figure 3. Ball-screw degradation and diagnostic-indicator map linking preload loss, pitting, scoring, backlash, stiffness loss, and lubrication film breakdown to measurable condition indicators.

2.4. Durability validation, confounders, and evidence integration

Published actuator-control studies typically validate tracking accuracy, response quality, and controller robustness under defined laboratory conditions, whereas component-health studies emphasize fault detection, preload loss, friction modelling, and wear diagnosis [1–5,9,17,21–24,29–32,40–42]. Recent control and estimation research offers two further perspectives relevant to durability validation. Cai et al. [44] combined an observer with online error-bound updating and a robust model predictive controller for vehicle trajectory tracking, and validated it in hardware-in-the-loop and real-vehicle tests; this shows that control performance claims become credible only when estimation uncertainty is bounded and the system is tested under realistic disturbances. Chen et al. [45] addressed fast anomaly detection and joint state estimation for perturbed nonlinear systems with prolonged output anomalies, which is relevant where sensor or test-stand anomalies persist rather than appear as isolated outliers. Both perspectives are pertinent to the present dataset, in which invalid stand sequences and an anomalous baseline current run had to be identified and excluded before pre/post comparison. Industrial durability validation sits between these traditions. It must decide whether a design can

continue to satisfy functional requirements after long-cycle exposure, while also preserving evidence of motor replacements, test-sequence revisions, omitted observations, and teardown distress. This is why the present manuscript does not reduce the durability result to either a pass/fail statement or a single wear metric. Instead, it frames functional measurements, motor history, data-treatment decisions, and teardown observations as separate but interacting evidence streams. These interacting evidence streams create the basis for the research gap summarized in the following section.

2.5. Research gap

The reviewed literature establishes four mature but only partly connected knowledge streams: shift-actuator control, direct-drive gear-shift mechanisms, ball-screw friction/preload diagnostics, and condition monitoring through current or vibration features. What remains less visible is an anonymized framework for interpreting multi-million-cycle Gear Shifter durability when only aggregate pre/post statistics are available and when the test history includes replacement motors, run-in changes, invalid observations, and teardown damage. The present study addresses that integration gap. It does not claim that no comparable industrial programme exists; rather, it converts a specification-driven validation report into a scientifically bounded durability-performance analysis that separates retained function, unresolved motor-design validation, measurement-process limitations, and physical distress.

Taken together, the literature streams summarized in Figures 1–3 show that actuator-control research, current-based diagnostics, and ball-screw prognostics and health management (PHM) each address a different part of the validation problem. Figure 4 therefore summarizes the remaining gap: integrating these strands when industrial durability data are aggregate, partially censored, and accompanied by teardown evidence.

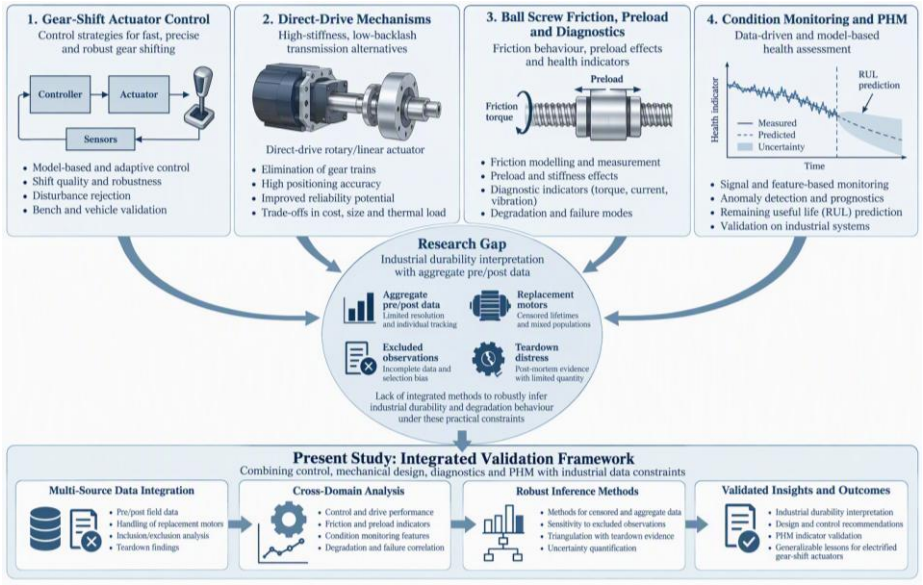


Figure 4. Literature streams converging to the research gap and motivating the integrated validation framework used in this study. PHM, prognostics and health management.

The literature review shows that actuator-control studies and component-health studies address important but different parts of the Gear Shifter validation problem. The methods section therefore defines the available system description, measured responses, sample structure, and confounding events before presenting results.

3. Materials and Methods

3.1. System and terminology

3.1.1. System description and terminology

The electromechanical Gear Shifter is used for medium-duty transmission applications. The designation "X axis" is reported here as rail-selection motion because the source material explicitly identified this direction with rail movement. The source designation "Y axis" is reported as gear-engagement motion. "Gear Shifter" replaces the proprietary programme term throughout. The mechanism included independent motor-driven motion paths and ball-screw elements acting through a shift finger. Detailed proprietary geometry, grade-specific material chemistry, lubricant trade name, calibration files, controller software, and supplier identity were unavailable for publication; therefore, the following description reports only non-proprietary architecture-level information. The source programme described the architecture as reduced-hysteresis, but no direct hysteresis metric or comparator was available in the anonymized dataset; consequently, reduced hysteresis is not treated as a demonstrated outcome in this paper.

3.1.2. Geometry and architecture definition

The device was treated as a two-axis linear actuation module with separate rail-selection and gear-engagement motion paths. Each motion path was driven by an electric motor and translated rotary output into linear shift-finger displacement through a ball-screw-based mechanical conversion stage. The shift finger transmitted output force to the transmission shift interface. The exact ball-screw lead, screw diameter, ball diameter, nut configuration, bearing stack, shift-finger offset, guide-rail spacing, backlash targets, ball-circuit layout, end-stop geometry, housing envelope, and attachment-hole pattern were intentionally not disclosed. For interpretation, the important geometry features were the presence of independent linear travel paths, ball-screw load transfer, thrust-washer interfaces, and constrained shift-finger stroke limits.

3.1.3. Materials and surface interfaces

Material details were not available at drawing level. The analysis therefore uses functional material categories rather than proprietary specifications. The ball-screw and rolling elements were treated as hardened rolling-contact components; the nut, thrust-washer interfaces, bearing supports, and shift-finger load path were treated as mechanically loaded metallic interfaces; and the housing and bracket structure were treated as structural support components. Because teardown evidence included ball-screw pitting and thrust-washer pitting/scoring, the most relevant material-interface considerations were rolling-contact fatigue resistance, surface hardness, finish, lubrication film formation, contact stress, fretting tendency, and corrosion protection. No chemical composition, heat-treatment depth, hardness traverse, coating description, surface-roughness value, or residual-stress measurement was available for inclusion.

3.1.4. Lubrication specification and service assumptions

The source dataset did not provide lubricant grade, base-oil type, thickener chemistry, viscosity, additive package, fill quantity, relubrication interval, contamination limits, or temperature-viscosity characterization. Lubrication is therefore described only as a boundary condition affecting interpretation. The ball-screw elements, thrust contacts, bearing supports, and sliding/rolling interfaces were assumed to operate with the lubricant state supplied during validation. Any post-durability change in force, current, velocity, or travel may have been influenced by run-in, lubricant redistribution, local film breakdown, contamination, thermal history, or grease migration. For this reason, the manuscript treats lubrication as a confounding factor rather than as a controlled explanatory variable.

3.1.5. Control calibration and measurement boundary

Controller calibration parameters were not included in the anonymized dataset. The study therefore does not disclose command profiles, current limits, torque constants, speed-loop gains, position-loop gains, acceleration limits, jerk limits, endpoint detection logic, diagnostic thresholds, anti-backlash compensation, or motor commutation details. The validation is interpreted at the measured-output level: shift-finger force, no-load velocity, breakaway current, half-travel, and half-shift time. Breakaway current is reported as a system-level indicator of torque demand at motion initiation, not as a

calibrated coefficient of friction. The run-in/repeatability revision described in Section 3.5 is treated as a measurement-process change because it could alter apparent current and timing behavior without requiring a geometric or material change.



Figure 5. Integrated validation architecture linking rail-selection and gear-engagement actuation, pre/post parametric measurements, durability exposure, teardown evidence, and major confounders.

3.2. Validation sequence

3.2.1. Test sequence and procedural controls

The validation sequence comprised four stages: (1) baseline parametric characterization of rail-selection and gear-engagement responses; (2) function-specific durability exposure applied primarily in either rail-selection or gear-engagement motion; (3) post-durability characterization using the same response definitions; and (4) teardown and visual inspection of selected assemblies. Gear-engagement durability reached 8.4 million shifts, described in the source as two nominal service lives. Measurements were organized by durability group, functional motion, response, and pre- or post-durability condition. Recorded responses were shift-finger force, no-load velocity, breakaway current, half-travel, and half-shift time. Following identification of a repeatability concern, three preliminary test-series runs were added before recorded measurements; tests initiated before that revision were retained and are identified as a procedural confounder. Breakaway-current records were excluded only when the stand moved the linear mechanism before current application. The available anonymized report did not retain the detailed cycle waveform, load spectrum, dwell, test frequency, environmental and temperature conditions, lubricant replenishment, instrumentation model, calibration status, sensor resolution, acquisition rate, or stopping criteria. These unavailable details are not reconstructed; their absence limits independent replication and is addressed explicitly in Section 5.7.

3.2.2. Reproducibility and reporting controls

To make the analysis reproducible from the available evidence, each result was assigned to one of two durability groups (rail-selection or gear-engagement), one measured motion (rail-selection or gear-engagement), one response variable, and one test condition (pre- or post-durability). Aggregate percentage change was calculated consistently as 100 × (post-test mean − pre-test mean)/pre-test mean. Observation counts were treated as measurement counts rather than independent specimen counts. No missing statistic was imputed, no excluded current record was reinstated, and no post-test value obtained with a replacement motor was interpreted as evidence for survival of the original development motor. Results for which raw pairing, uncertainty, or instrument metadata were unavailable were retained as descriptive evidence only.

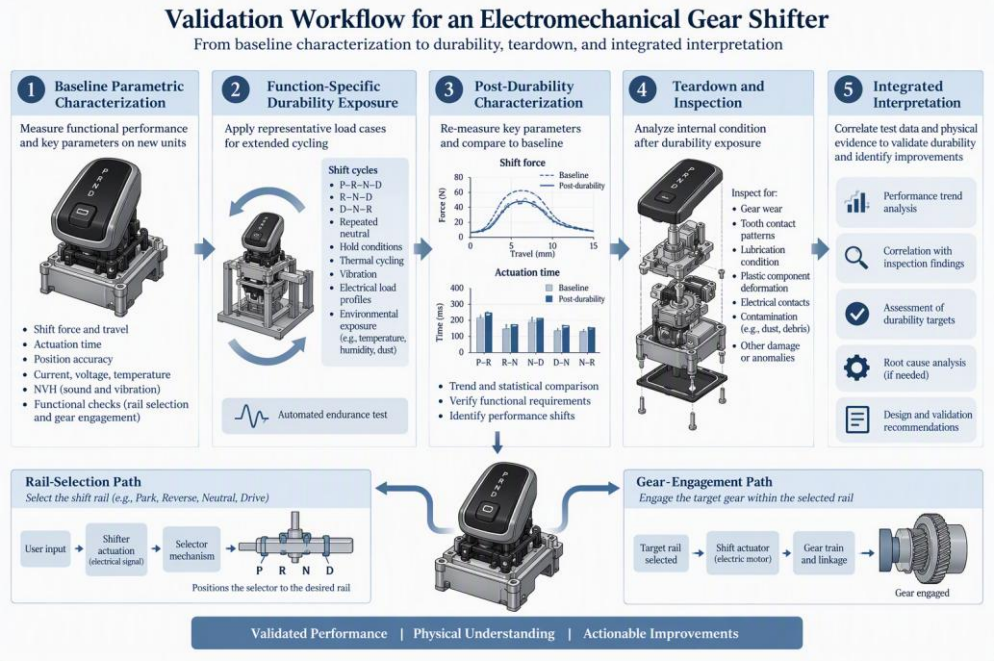


Figure 6. Validation workflow showing baseline characterization, function-specific durability exposure, post-durability characterization, teardown inspection, and integrated interpretation.

3.3. Measured responses

Table 1. Measured responses, operational definitions, and SI units used in this study.

Response	Definition used in this study	SI unit (source unit)
Shift-finger force	Output force measured for the selected functional motion	N (lbf)
No-load velocity	Maximum shift-finger velocity without external constraint	mm/s (in/s)
Breakaway current	Motor/shifter current required to initiate motion from rest	A
Half-travel	One-half of maximum unconstrained shift-finger travel	mm (in)
Half-shift time	Time associated with one-half stroke	s

All quantities in this manuscript are reported in SI units. Values recorded in U.S. customary units in the source dataset were converted using 1 lbf = 4.44822 N for force and 1 in = 25.4 mm for displacement and velocity (1 in/s = 25.4 mm/s); converted force values are rounded to the nearest newton and converted velocity dispersion values to 0.1 mm/s. Breakaway current is reported in amperes (A) and half-shift time in seconds (s). Percentage changes are unaffected by unit conversion.

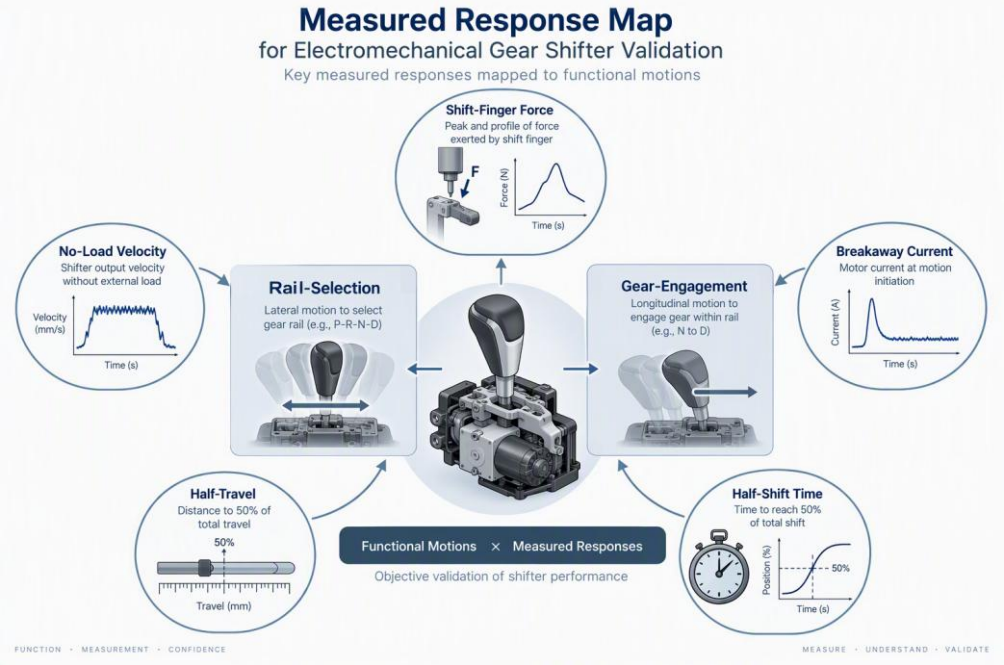


Figure 7. Measured response map linking rail-selection and gear-engagement functions to force, velocity, breakaway current, half-travel, and half-shift-time measurements.

3.4. Sample structure and data treatment

The report supplied aggregate statistics rather than raw traces. Sample counts differed by response because each assembly and motion direction could generate repeated observations. Therefore, N represents the number of measurements included in each summary, not the number of independent assemblies or statistically independent specimens. The durability groups should not be interpreted as balanced randomized cohorts. Percentage change was calculated as 100(Post mean − Pre mean)/Pre mean. No paired t-test, analysis of variance, confidence interval, process-capability index, or reliability model was calculated because the necessary raw observations, pairing identifiers, independence structure, and complete censoring history were unavailable.

3.5. Deviations, exclusions, and confounders

- Eight of twelve development motors failed before completion of gear-engagement durability; most post-test measurements in that group therefore used replacement motors.
- One investigated end-of-life assembly experienced a development-motor failure after approximately 7.11 million shifts and completed the remaining exposure with a production replacement motor.
- A run-in/repeatability issue was identified early. The procedure was revised to add three preliminary test-series runs before recorded measurements, but some durability testing had begun before this revision.
- Breakaway-current observations were omitted when the test stand moved the linear mechanism before current was applied. Four post-test observations were removed in one durability group and two in another.
- An anomalous baseline breakaway-current run generated unusually high variability; no recurring assembly problem was reported.
- Build-level design modifications existed between validation stages. They are described only functionally because part numbers and detailed traceable geometry have been removed.

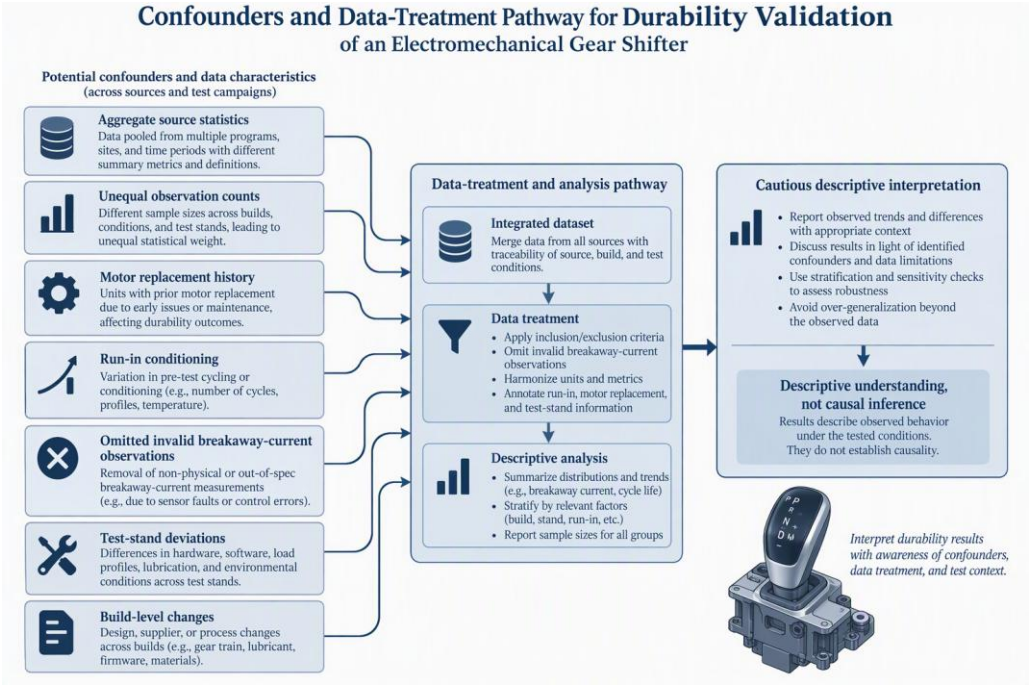


Figure 8. Confounders and data-treatment pathway emphasizing aggregate statistics, unequal observation counts, motor replacement, run-in conditioning, excluded observations, test-stand deviations, and descriptive interpretation.

3.6. Scientific boundary and comparability of test conditions

The test conditions were not uniform across the complete programme, and the scientific boundary of the study is therefore stated explicitly. The unit of analysis is the output of the mechanical Gear Shifter—shift-finger force, no-load velocity, half-travel, and half-shift time—measured with the same response definitions before and after durability exposure. The motor population, run-in state, lubricant condition, and thermal environment are treated as uncontrolled or partially controlled factors, not as experimental variables. In particular, all twelve motors fitted at the start of gear-engagement durability were development motors, but the anonymized dataset does not confirm that they came from a single build lot or that they were matched in winding resistance, torque constant, or no-load speed. After eight of these motors failed, most post-test measurements in that group were obtained with replacement motors, including at least one production-level motor. Motor-to-motor variation is therefore an acknowledged source of variance in the current, velocity, and timing responses, and the pre- and post-test motor populations are not identical. Table 3 summarizes the control status of each factor and its consequence for interpretation.

Table 3. Control status of test conditions and their consequence for interpretation.

Factor	Condition in this programme	Control status	Consequence for interpretation
Motor population	12 development motors; 8 failed during gear-engagement durability; most post-test measurements used replacement motors (at least one production-level)	Not controlled; changed between pre- and post-test	Current, velocity, and timing changes cannot be attributed to the shifter alone; original-motor durability is not validated

Run-in conditioning	Three preliminary test-series runs added after a repeatability concern; some tests started before the revision	Partially controlled	Pre/post differences may include conditioning effects; treated as a confounder
Lubrication	Lubricant state as supplied; grade, fill quantity, and replenishment not retained	Not documented	Treated as a boundary condition; no tribological rate or friction-coefficient inference
Environment and temperature	Ambient and component temperature history not retained	Not documented	Thermal effects on current and velocity cannot be excluded
Test-stand behaviour	Stand-sequence deviations; invalid breakaway-current records excluded (four and two post-test records)	Controlled by a predefined exclusion rule	Reduced counts disclosed; no reinstatement or imputation
Response definitions and calculation	Identical definitions pre and post; common percentage-change formula	Controlled	Aggregate pre/post comparisons are internally consistent
Build level	Build-level design modifications between validation stages	Partially documented	Described functionally only; not treated as a test variable

Within this boundary, the dataset retains reference value in two respects. First, it documents output-function retention after up to 8.4 million shifts under a service-representative history in which motor substitution, run-in, and lubricant redistribution occurred, as they may in field operation. Second, it provides the magnitude and direction of aggregate pre/post changes (Table 2) against which a controlled follow-up programme can be sized. The dataset is not a reference for tribological wear rates, friction coefficients, or motor life. A controlled follow-up should use motors from a single build lot characterized for winding resistance, torque constant, and no-load speed before test; a fixed run-in procedure applied before every recorded measurement; a documented lubricant grade, fill quantity, and replenishment rule; controlled and logged ambient and component temperature; and specimen-level logging of force, current, displacement, and velocity at predefined durability intervals.

3.7. Quantitative basis for performance-retention claims

The source programme assessed the measured responses against internal design specifications. The numerical specification limits, allowable degradation limits, and minimum functional requirements are proprietary and could not be released with the anonymized dataset. Consequently, this manuscript does not claim specification compliance as an independently verifiable result. "Performance retention" is instead used in a defined, baseline-referenced sense with three quantitative checks. First, an adverse direction is assigned to each response: a decrease in force, velocity, or half-travel, and an increase in breakaway current or half-shift time, represents functional loss. Second, the largest adverse aggregate mean change across the four durability-group/motion combinations is reported for each response. Third, where dispersion data exist, a

descriptive lower-tail indicator, mean − 2SD, is compared before and after durability to check whether the weaker part of the population deteriorated even when the mean did not. This indicator is not a tolerance limit and assumes only an approximately symmetric distribution; it is used as a screening signal. Table 4 applies these checks to the values in Table 2.

Table 4. Baseline-referenced retention basis derived from Table 2. Adverse direction denotes the direction of change that represents loss of function.

Response	Adverse direction	Range of aggregate mean change	Largest adverse mean change (condition)	Dispersion / lower-tail check
Shift-finger force	Decrease	−0.8% to +18.3%	−0.8% (GE durability, GE motion)	GE/GE: SD 187 → 267 N (+43%); mean − 2SD 698 → 529 N (−24.2%)
No-load velocity	Decrease	−1.0% to +2.1%	−1.0% (RS durability, GE motion)	GE/GE: SD 2.5 → 7.6 mm/s (×3.0); means not reported, lower tail not computable
Half-travel	Decrease	−1.7% to −0.3%	−1.7% (RS durability, GE motion)	Not reported
Half-shift time	Increase	−4.6% to −1.0%	None (all changes favourable)	Not reported
Breakaway current	Increase	−8.5% to −3.0%	None (all changes favourable; confounded, see Section 5.2)	Baseline SD 0.52 A (RS/RS) influenced by one anomalous run

RS, rail-selection; GE, gear-engagement. Condition is given as durability group, measured motion. Mean − 2SD is a descriptive lower-tail indicator, not a tolerance limit.

On this basis, retention is claimed only in the following bounded sense: across all response-condition combinations, the largest adverse aggregate mean change was 1.7%, and no adverse mean change occurred in breakaway current or half-shift time. The check also shows the limitation of mean-based retention. In the gear-engagement force response after gear-engagement durability, the mean changed by only −0.8%, yet the lower-tail indicator decreased by 24.2%, which is consistent with the source attribution of low post-test force in two assemblies to thrust-washer distress. Whether a 1.7% mean reduction or a 24% lower-tail reduction remains within design limits cannot be established from the publishable data; such judgements require the specification margins withheld from this dataset.

The preceding section clarifies why the results must be read as descriptive aggregate evidence. The results therefore report percentage changes, dispersion, omitted observations, and teardown findings together rather than isolating any single response variable as the sole measure of durability success.

4. Results

4.1. Aggregate descriptive results

Table 2 is the single source for every quantitative value reported in Sections 4.1–4.5 and plotted in Figures 9 and 10. Absolute pre- and post-test means were available only for shift-finger force (all four conditions) and for half-shift time in gear-engagement motion after gear-engagement durability; for the remaining responses, only percentage changes and, in some cases, dispersion statistics were retained. Figure 9 therefore plots absolute means only where Table 2 reports them, and Figure 10 plots the percentage-change column of Table 2.

Table 2. Consolidated aggregate descriptive results available in the anonymized source dataset.

Durability group	Measured motion	Response	Pre mean	Post mean	Change	Other reported statistics or notes
Rail-selection	Rail-selection	Force (N)	943	1081	+14.6%	
Rail-selection	Gear-engagement	Force (N)	1117	1130	+1.2%	
Gear-engagement	Rail-selection	Force (N)	899	1063	+18.3%	
Gear-engagement	Gear-engagement	Force (N)	1072	1063	−0.8%	SD: 187 N pre, 267 N post; post-test N = 71
Rail-selection	Rail-selection	No-load velocity (mm/s)	Not reported	Not reported	0.0%	
Rail-selection	Gear-engagement	No-load velocity (mm/s)	Not reported	Not reported	−1.0%	
Gear-engagement	Rail-selection	No-load velocity (mm/s)	Not reported	Not reported	−0.9%	
Gear-engagement	Gear-engagement	No-load velocity (mm/s)	Not reported	Not reported	+2.1%	SD: 2.5 pre, 7.6 post; range: 12.7 pre, 30.5 post
Rail-selection	Rail-selection	Half-travel (mm)	Not reported	Not reported	−0.4%	
Rail-selection	Gear-engagement	Half-travel (mm)	Not reported	Not reported	−1.7%	
Gear-engagement	Rail-selection	Half-travel (mm)	Not reported	Not reported	−0.3%	
Gear-engagement	Gear-engagement	Half-travel (mm)	Not reported	Not reported	−1.0%	Post-test N = 70
Rail-selection	Rail-selection	Breakaway current (A)	Not reported	Not reported	−8.5%	Baseline SD = 0.52 A; maximum = 5.23 A
Rail-selection	Gear-engagement	Breakaway current (A)	Not reported	Not reported	−3.0%	
Gear-engagement	Rail-selection	Breakaway current (A)	Not reported	Not reported	−4.3%	One reduced post-test count was 106 or 212; row assignment unavailable
Gear-engagement	Gear-engagement	Breakaway current (A)	Not reported	Not reported	−4.3%	One reduced post-test count was 106 or 212; row assignment unavailable
Rail-selection	Rail-selection	Half-shift time (s)	Not reported	Not reported	[0.45 Sec]	
Rail-selection	Gear-engagement	Half-shift time (s)	Not reported	Not reported	[0.22]	
Gear-engagement	Rail-selection	Half-shift time (s)	Not reported	Not reported	[0.25 Sec]	
Gear-engagement	Gear-engagement	Half-shift time (s)	0.131	0.125	−4.6%	Largest reported timing change; only timing condition with absolute means

Table 2 consolidates every numerical aggregate result retained in the manuscript source. "Not reported" indicates that the anonymized material available for this submission did not provide the corresponding mean, count, dispersion, minimum, median, maximum, or range; no missing value was estimated or back-calculated. The reduced post-test breakaway-current counts were 106 and 212 for two conditions, but the available narrative did not identify their unique row assignment; they are therefore disclosed without speculative allocation. Half-shift time decreased in all four durability-group/motion combinations (range −1.0% to −4.6%); the individual percentage change for each combination is listed in Table 2 so that every timing value plotted in Figure 10 can be traced to the table.

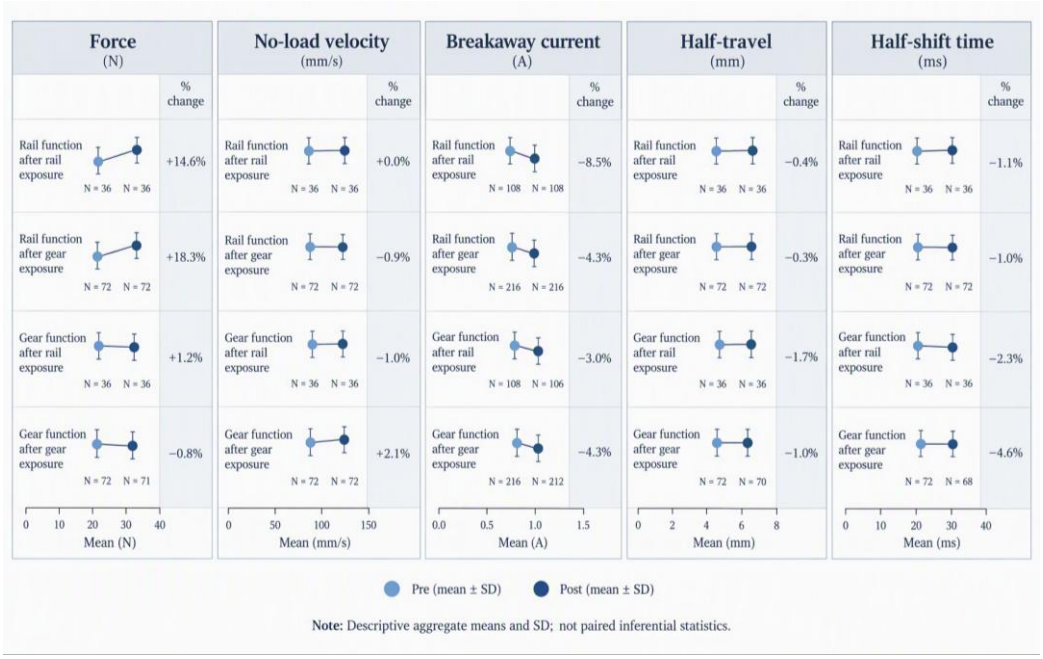


Figure 9. Aggregate pre/post means and standard deviations for the responses whose absolute values are reported in Table 2: shift-finger force (four durability-group/motion conditions) and gear-engagement half-shift time after gear-engagement durability. Responses for which Table 2 reports only percentage change are not plotted as absolute values. Values are descriptive aggregate summaries rather than paired inferential statistics.

4.2. Force

Rail-selection force increased from 943 to 1081 N after rail-selection durability (+14.6%) and from 899 to 1063 N after gear-engagement durability (+18.3%). Gear-engagement force changed from 1117 to 1130 N (+1.2%) after rail-selection durability and from 1072 to 1063 N (–0.8%) after gear-engagement durability. Dispersion in the latter condition increased from 187 to 267 N, and the post-test count decreased from 72 to 71. The source associated low post-test force observations in two assemblies with thrust-washer pitting and scoring, but specimen-level data were not available to quantify that relationship.

4.3. Velocity and timing

No-load velocity remained close to baseline. Rail-selection velocity changed by 0.0% and –0.9% in the two durability groups. Gear-engagement velocity changed by –1.0% after rail-selection durability and +2.1% after gear-engagement durability. The standard deviation for the last condition increased from 2.5 to 7.6 mm/s, with a range increase from 12.7 to 30.5 mm/s reported in the source. One assembly's increased gear-engagement velocity variation was considered plausibly related to observed ball-screw pitting; this remains a source interpretation rather than a demonstrated causal relation. Half-shift time decreased modestly in all four combinations, with the largest aggregate change in gear-engagement motion after gear-engagement durability (0.131 to 0.125 s, –4.6%).

4.4. Travel

Half-travel remained close to baseline. Rail-selection half-travel decreased by 0.4% and 0.3% after rail-selection and gear-engagement durability, respectively. Gear-engagement half-travel decreased by 1.7% after rail-selection durability and 1.0% after gear-engagement durability. The gear-engagement post-test count in the latter condition was 70 rather than 72. Without raw paired measurements and measurement uncertainty, these small aggregate changes should be described as retention with modest downward shifts, not as verified dimensional wear.

4.5. Breakaway current

Breakaway-current means decreased in every condition: –8.5% and –4.3% for rail-selection motion, and –3.0% and –4.3% for gear-engagement motion. The rail-selection baseline under rail-selection durability had a high standard deviation (0.52 A) and maximum (5.23 A) attributed to one anomalous run. Post-test counts were reduced to 106 and 212 in two conditions because invalid stand sequences were excluded. Current reduction is consistent with lower system resistance, but the experiment cannot distinguish running-in, lubrication effects, preload change, replacement-motor characteristics, or test-procedure effects.

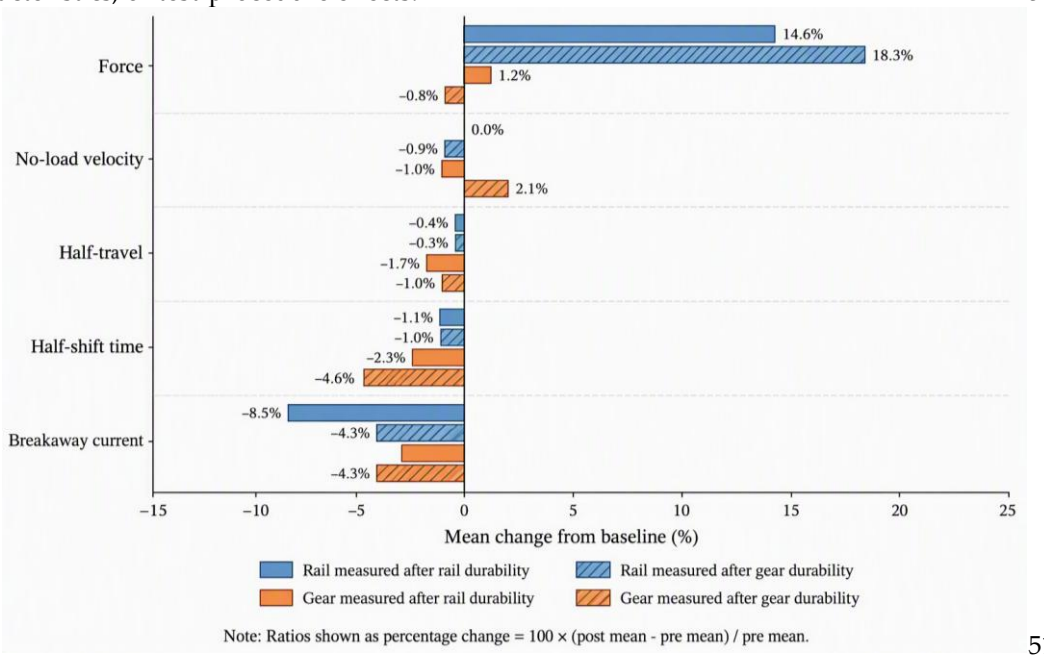


Figure 10. Percentage-change summary for Sections 4.2–4.5. Each bar corresponds to one row of the "Change" column in Table 2, calculated as 100 × (post mean − pre mean) / pre mean; positive values indicate aggregate increases and negative values indicate aggregate decreases.

4.6. End-of-life functional evidence and physical distress

The end-of-life evidence is reported separately at three system boundaries. (i) Original-component survival: of the twelve development motors fitted at the start of gear-engagement durability, eight failed before completion and four completed the exposure, an observed completion fraction of 4/12 (33%). This is a descriptive count; it is not a reliability estimate and does not validate the original motor design. (ii) Replacement-system functionality: most post-test parametric measurements in the gear-engagement group, and a limited vehicle trial of one assembly, were obtained with replacement motors. That assembly experienced development-motor failure at approximately 7.11 million shifts, completed the remaining exposure with a production replacement motor, and operated without real or nuisance faults during the trial. These results show that the assembled shifter continued to function after motor substitution; they do not represent the original motor–shifter configuration. (iii) Mechanical-actuator durability: the baseline-referenced retention of force, velocity, half-travel, and half-shift time (Table 4) is the evidence for the mechanical Gear Shifter itself, with the qualification that the post-test

values include the influence of the replacement motors. Teardown of selected assemblies identified pitting/scoring at thrust-washer interfaces and pitting on the ball screw. These are qualitative visual observations; pit size, depth, area fraction, and location were not measured, and the damage was not linked specimen by specimen to the force, velocity, or current records. The observations therefore establish that internal distress coexisted with retained aggregate function, but not a validated degradation mechanism or progression rate.



Figure 11. Schematic representation (not a specimen photograph) of the damage locations recorded during teardown: ball-screw pitting and thrust-interface scoring. The figure indicates where distress was observed; it does not reproduce the measured appearance or extent of damage on any specific specimen and does not imply a validated degradation mechanism.

The results indicate overall functional retention, but their engineering meaning depends on how improvement-like trends, motor replacements, omitted observations, and physical distress are weighed together. The discussion therefore interprets the evidence through the validation question rather than through a single wear or performance metric.

5. Discussion

5.1. Performance retention versus apparent improvement

The primary result is aggregate retention of the measured output functions, not universal improvement. Force increases, shorter aggregate shift time, and lower breakaway current may appear beneficial, but the same signatures can arise from running-in, lubricant redistribution, reduced preload, motor replacement, or measurement-process changes. Because the motor population and conditioning procedure changed, the data cannot uniquely attribute apparent improvement to the mechanical architecture. The source programme's reduced-hysteresis designation is therefore treated as a design description rather than a quantitatively validated outcome.

5.2. Interpretation of current as a friction proxy

Breakaway current is used here as an actuator-system indicator of torque demand at motion initiation, not as a calibrated friction coefficient or direct wear measurement. A lower current mean may be consistent with reduced apparent resistance, but the available data cannot separate running-in, lubrication redistribution, preload change, replacement-motor characteristics, external load effects, or test-procedure changes.

5.3. Ball-screw and thrust-interface distress

Ball-screw pitting is consistent with rolling-contact surface fatigue or wear damage, and contemporary literature shows that pitting progression and preload/rigidity loss can be detected through direct or indirect condition indicators [10–17,25–34,36]. Nevertheless, the available evidence is qualitative. No pit geometry, microscopy, hardness, lubricant analysis, contact stress, preload, or surface-roughness data were available. Likewise, thrust-washer scoring can coincide with elevated friction or intermittent force loss, but the

source data do not establish the sequence of damage initiation. The manuscript therefore uses "associated with" or "observed with," not "caused by."

5.4. Design-validation significance

A single pass/fail statement would conceal four important findings: the Gear Shifter retained useful output performance; development motors experienced substantial durability failures; internal distress was present despite retained function; and measurement-process uncertainty affected interpretation. The integrated approach makes these distinctions visible (Table 5). This is directly relevant to engineering release decisions because actuator hardware, motor design, measurement procedure, and failure-detection strategy can require different corrective actions.

Table 5. Evidence-integration summary showing how performance retention, motor durability history, component distress, and measurement validity inform design-validation interpretation and corrective-action decisions.

Evidence stream	Observation	Supports	Does not support	Corrective action
Performance retention	Force, velocity, half-travel, and half-shift time retained at aggregate level after up to 8.4 million shifts	Functional retention of the mechanical Gear Shifter	Specimen-level degradation rates	Retain output-function acceptance criteria; add specimen-level logging
Motor durability history	8 of 12 development motors failed; replacement motors used for most post-test measurements	Need to revise the development-motor design	Survival of the original motor design	Motor redesign and separate motor qualification
Component distress	Ball-screw pitting; thrust-washer pitting/scoring	Internal distress coexisting with retained function	Causal wear mechanism or progression rate	Surface, contact, and lubrication review; quantitative teardown metrology
Measurement validity	Run-in revision; excluded current records; aggregate statistics only	Descriptive pre/post comparison	Inferential statistics or friction attribution	Fixed conditioning procedure; retention of raw paired data

5.5. Comparison with current literature

Control-oriented Gear Shifter literature demonstrates precise trajectory tracking and disturbance rejection [1–5,17–19], while ball-screw research provides increasingly sophisticated friction, preload-loss, wear, and diagnostic models [6–17,25–36]. The present study complements those strands with long-cycle system evidence. Its scientific value is

strongest as a field-relevant validation dataset and weakest as a causal tribology experiment. Future work should connect specimen-level current, force, displacement, and velocity histories to measured pit growth, preload, and lubricant condition at predefined durability intervals.

5.6. Original-motor durability and replacement-motor system evidence

The durability evidence supports different conclusions at different system boundaries. At the original-motor boundary, eight failures among twelve development motors demonstrate that the programme did not establish satisfactory survival of that motor population through the gear-engagement exposure. At the replacement-motor system boundary, completion of the remaining durability exposure and the limited vehicle trial demonstrate that the assembled shifter could continue to function after motor substitution. At the mechanical-shifter boundary, retained aggregate force, velocity, travel, and timing indicate that the measured output functions remained available despite motor attrition and observed internal distress. These statements are not interchangeable: post-test measurements obtained with replacement motors cannot be used to validate the original motor design, while original-motor failures do not by themselves establish loss of the mechanical shifter's output capability.

5.7. Limitations

This study is limited by the structure and completeness of the anonymized industrial dataset. Raw paired observations and specimen identifiers were unavailable, so repeated measurements could not be separated from statistically independent specimens and inferential paired analysis was not justified. Observation counts differed among responses, and invalid breakaway-current records were excluded after documented stand-sequence deviations. Eight development motors failed, most post-durability measurements in the gear-engagement group used replacement motors, and the motor population therefore changed between baseline and post-test characterization. The run-in procedure was revised after some durability tests had started. Instrument models, calibration records, sensor resolution, acquisition rate, measurement uncertainty, detailed cycle waveform, load spectrum, dwell, temperature, lubricant condition, and environmental history were not retained in the publication dataset. Teardown observations were qualitative and were not supported by pit geometry, microscopy, hardness, preload, surface-roughness, contact-stress, or lubricant analyses. The control status of each of these factors is summarized in Table 3. The results consequently support descriptive system-level retention and evidence integration, but not specimen-level degradation rates, causal wear attribution, reliability estimation, direct hysteresis reduction, or independent replication of the original test programme.

5.8. Quantitative conclusions justified by the data

Because Table 2 contains mostly percentage changes, unequal counts, and limited dispersion data, and because repeated observations cannot be separated from independent specimens, the quantitative conclusions that remain justified are limited. Table 6 classifies each candidate conclusion according to whether the available data support it.

Table 6. Quantitative conclusions supported and not supported by the aggregate dataset.

Candidate conclusion	Status	Basis or missing information
Direction and magnitude of aggregate mean change for each response and condition	Supported (descriptive)	Table 2, common percentage-change formula
Largest adverse aggregate mean change of 1.7%; no adverse change in current or timing	Supported (baseline-referenced)	Table 4

Increased dispersion of gear-engagement force and velocity after gear-engagement durability	Supported (descriptive)	SD 187 → 267 N; SD 2.5 → 7.6 mm/s
Observed completion of 4 of 12 development motors through gear-engagement durability	Supported (count only)	Motor history; no failure times for a life distribution
Compliance with design specification limits	Not verifiable in this publication	Specification limits proprietary
Statistical significance of pre/post differences	Not supported	No raw paired data; independence structure unknown
Specimen-level degradation trajectories or rates	Not supported	No interval measurements or specimen identifiers
Reliability or failure probability of the shifter or motor	Not supported	No failure times, censoring history, or independent specimens
Causal link between teardown damage and performance change	Not supported	Damage not quantified or matched to specimen records

5.9. Transferable contribution

This study does not develop a new durability model, diagnostic criterion, or reliability-estimation method, and it is not presented as one. Its contribution is a reporting and interpretation procedure for actuator durability validation when only aggregate industrial data are available, which can be applied to other electromechanical actuators. The procedure has three elements. First, a boundary-separation rule: original-component survival, replacement-system function, and mechanical-actuator retention are reported as separate claims, and evidence obtained at one boundary is not used to support a claim at another. Second, a baseline-referenced retention check: each response is assigned an adverse direction, the largest adverse aggregate change is reported, and a lower-tail dispersion screen is applied. In this dataset the screen revealed that a −0.8% mean change in gear-engagement force concealed a 24% reduction in the lower-tail indicator, a finding that a mean-only pass/fail assessment would have missed. Third, a minimum data set for future studies: specimen identifiers and raw paired observations; normalized specification margins; motor lot and electrical characterization; a fixed run-in procedure; documented load, frequency, dwell, temperature, and lubricant condition; instrument calibration and uncertainty; interval measurements during durability; and quantitative teardown metrology. With these data, the same framework can be extended to inferential statistics, life-distribution modelling, and degradation-to-performance correlation.

6. Conclusions

- Relative to baseline, the Gear Shifter retained rail-selection and gear-engagement force, no-load velocity, half-travel, and half-shift time after function-specific durability exposure of up to 8.4 million shifts: the largest adverse aggregate mean change was 1.7% (half-travel), and no adverse mean change occurred in breakaway current or half-shift time. Compliance with the proprietary design specifications cannot be verified from the publishable data.
- Rail-selection force increased, while gear-engagement force remained approximately stable in the aggregate (−0.8% to +1.2%). After gear-engagement durability, however,

gear-engagement force dispersion increased by 43% and its lower-tail indicator (mean − 2SD) decreased by 24%, indicating that mean-based retention can conceal degradation in weaker units. Travel changes were small and shift-time means decreased modestly.

- Breakaway-current means decreased, but the trend cannot be assigned uniquely to reduced friction because of motor replacement, running-in, preload/lubrication effects, exclusions, and measurement-process changes.
- Thrust-washer pitting/scoring and ball-screw pitting show that retained actuator-level performance did not imply absence of internal damage.
- The evidence supports different conclusions at different system boundaries. Original-component survival was not demonstrated: only 4 of 12 development motors completed gear-engagement durability. Replacement-system functionality was demonstrated for the assemblies that completed exposure and for one vehicle trial. Mechanical-actuator retention is supported at the aggregate level, but the post-test measurements include the influence of replacement motors.
- The study contributes a transferable reporting and interpretation procedure—boundary separation, a baseline-referenced retention check with a lower-tail screen, and a minimum data set—rather than a new durability or reliability model. Specimen-level degradation rates, statistical significance, reliability, and damage–performance causality are not supported by the aggregate data (Table 6).
- These conclusions are bounded to the measured output functions of the mechanical Gear Shifter under the documented test history. Because the motor population, run-in state, lubrication, and environmental conditions were not uniformly controlled (Table 3), the results are not a reference for tribological wear rates, friction coefficients, or motor life.

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Clinical trial number: Not applicable. This study involved mechanical-component durability testing and did not involve humans or animals.

Ethics: Ethical approval was not required for this study as it utilized publicly available/anonymized data

Consent to Participate: Informed consent was obtained from all individual participants involved in the study to participate.

Consent to Publish: The participants provided written informed consent for the publication of their details and/or accompanying images.

Institutional Review Board Statement: Not applicable. This study involved mechanical-component durability testing and did not involve humans or animals.

Informed Consent Statement: Not applicable.

Data Availability Statement: The aggregate data supporting the reported findings are presented within the article. Raw specimen-level records, proprietary geometry, calibration files, controller parameters, supplier information, and detailed test-programme records are not publicly available because the publication dataset was anonymized and subject to proprietary restrictions.

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