JOURNAL OF
MULTIDISCIPLINARY
SCIENCES AND INNOVATIONS

VOLUME 5, ISSUE 05
MONTHLY JOURNALS

ISSN NUMBER: 2751-4390
IMPACT FACTOR: 9,08

RELIABILITY PREDICTION AND ERGONOMIC OPTIMISATION OF MANUAL LEVER SYSTEMS FOR DISABILITY-ADAPTED VEHICLES: AN EXPERIMENTAL AND MATHEMATICAL MODELLING APPROACH

Vokhobov R.A
Senior lecturer
Andijan State Technical Institute
Andijan, Uzbekistan
https://doi.org/10.5281/zenodo.20330850

Abstract

Mechanical lever systems that transfer foot-pedal functions to hand operation are the most widely deployed adaptive technology in retrofitted vehicles for drivers with lower-limb disabilities. Their premature failure or ergonomic inadequacy directly compromises driver safety, yet no locally validated reliability or ergonomic assessment framework exists in Central Asia. Objective: To quantify the reliability characteristics and ergonomic performance of a prototype dual-lever hand-control system through experimental testing and mathematical modelling, and to derive optimisation guidelines for future designs.

Keywords: hand-control lever; Weibull reliability; ergonomic index; adapted vehicle; mechanical transmission; Bowden cable; disability; vehicle retrofitting

1. Introduction

Globally, an estimated 15% of the population lives with some form of disability (WHO, 2023), and a substantial proportion of this group has lower-limb impairments that preclude operation of conventionally designed vehicle controls. In Uzbekistan, government statistics indicate a steady annual increase in the registered population of persons with disabilities. National policy instruments — including the New Uzbekistan Development Strategy for 2022–2026 and Government Resolution No. 183 of 2018 — have established a regulatory framework under which light vehicles may be retrofitted with hand-control systems, enabling persons with lower-limb pathologies to obtain driving licences and operate personal vehicles independently.

Among the various adaptive technologies available — joystick systems, electronic drive-by-wire controls, and voice-command interfaces — simple mechanical lever systems remain the most widely adopted in Uzbekistan's domestic retrofitting practice. Their prevalence is attributable to low manufacturing cost, compatibility with mechanical-gearbox vehicles produced by UzAuto Motors, straightforward installation, and ease of maintenance by locally available technicians. A typical dual-lever configuration provides separate left-hand operation of the clutch and right-hand combined operation of the accelerator and brake, replicating the functional scope of the three foot pedals present in a manually geared vehicle.

Despite widespread use, the reliability and ergonomic characteristics of domestically produced lever systems have not previously been subjected to rigorous quantitative assessment. Published literature on adaptive vehicle controls — including Nacpil et al. (2020) on electromyography-based systems, Bhatia et al. (2019) on smart systems for drivers with disabilities, and Messaoudene et al. (2010) on brake handwheel concepts for paraplegic drivers — predominantly addresses electronic or electromechanical technologies and does not provide reliability or ergonomic benchmarks for purely mechanical lever assemblies of the type used locally.

This gap is consequential. Mechanical lever systems that fail in service can cause loss of vehicle control, while ergonomically suboptimal designs increase driver fatigue and reduce the precision and speed of control inputs. Both outcomes adversely affect road safety for the driver and other road users. Furthermore, without validated reliability data, it is impossible to establish rational maintenance intervals, warranty periods, or service life declarations for these components.

Objective: This study aims to: (i) experimentally characterise the fatigue life of a prototype dual-lever hand-control system using accelerated cyclic loading; (ii) derive Weibull reliability parameters and predict service life under operational conditions; (iii) quantify ergonomic performance using a validated composite index; (iv) develop an analytical mechanical model of the lever-cable transmission to identify critical components; and (v) formulate specific design optimisation recommendations.

2. Materials and Methods

2.1 Prototype Description

The prototype dual-lever system consists of: a left-hand actuator lever (150 mm moment arm) connected via a Bowden cable to the clutch pedal push-rod; a right-hand actuator lever (160 mm moment arm) with a forward-pull linkage to the accelerator cable and a rearward-push linkage to the brake master cylinder push-rod; steel lever brackets welded to the steering column support; and 4.0 mm diameter steel wire rope within a 6.0 mm outer-diameter PVC-coated outer casing. All metal components were fabricated from St3sp structural steel. The system permits simultaneous operation by both a hand-impaired and a non-impaired driver, ensuring universal usability.

2.2 Mechanical Transmission Model

An analytical model was developed to determine the relationship between hand input force (F_{hand}) applied at the lever grip and the output force transmitted to the target control (F_{out}). For the brake circuit, the model is expressed as:

$$F_{out} = F_{hand} \cdot (L_{lever} / L_{cable\_arm}) \cdot \eta_{cable}$$

where L_{lever} is the lever moment arm (160 mm), L_{cable_arm} is the effective cable attachment arm (40 mm), and ηcable is the cable transmission efficiency. The efficiency factor was determined empirically by measuring input and output forces simultaneously using calibrated load cells at five cable routing angles (0°, 15°, 30°, 45°, 60°), yielding a mean value of $\eta cable = 0.91 \pm 0.02$.

Stress analysis of the lever-bracket weld joint was conducted analytically using beam bending theory, with the maximum bending moment computed for the 95th-percentile maximum one-hand push force of 240 N (ISO 11228-1:2003). Von Mises equivalent stress at the critical weld toe was 87.4 MPa, below the allowable fatigue stress of 120 MPa for St3sp steel at 10^7 cycles (GOST 14771). Cable casing wall hoop stress under combined axial cable tension and lateral reaction force was identified as the highest-stress condition in the cable sub-assembly.

2.3 Cyclic Loading Fatigue Test

The test bench comprised the complete prototype lever assembly mounted on a rigid steel frame, with servo-actuated loading applied to each lever grip by a linear actuator controlled by a programmable logic controller (PLC). The loading profile was designed to replicate realistic driving cycles: for the brake circuit, each cycle consisted of a 0.5 s application phase ($F_{hand} = 120$ N, consistent with moderate braking), followed by a 0.5 s return phase; for the clutch circuit, each cycle applied $F_{hand} = 80$ N over 0.8 s and returned over 0.4 s.

The durability test was conducted under nominal operating conditions. The hand-control mechanism was subjected to 100,000 cycles at 100% of the design force. Measurements were taken before and after the cyclic test to evaluate possible changes in the main structural and functional elements of the mechanism. The measured parameters included lever pivot wear, cable elongation, and the outer diameter of the cable casing. Lever pivot wear was measured using a micrometer with an accuracy of ±0.01 mm, cable elongation was measured using an extensometer with an accuracy of ±0.1 mm, and the outer diameter of the cable casing was measured using a digital caliper with an accuracy of ±0.02 mm.2.4 Weibull Reliability Analysis

The two-parameter Weibull reliability function was fitted to the accumulated wear data. Progressive cable elongation was treated as the failure-relevant degradation parameter, with the critical threshold set at 3.0 mm elongation (corresponding to a 15% reduction in brake actuation force margin). Maximum likelihood estimation was used to determine β (shape parameter) and η (characteristic life parameter) from the Phase 1 and Phase 2 measurement series combined. The B10 life (10th percentile failure cycle count) was calculated as:

$$N\_{B10} = \eta \cdot [-\ln(0.90)]\text{^}(1/\beta)$$

2.5 Ergonomic Evaluation

Ergonomic performance was evaluated by four assessors (two human factors specialists and two vehicle adaptation engineers) using a structured scoring protocol. Each assessor rated four sub-dimensions on a 0–1 scale: Ereach (spatial adequacy of lever position relative to 5th–95th percentile reach envelopes per ISO 7250-1:2017), Eforce (force adequacy relative to ISO 11228-1 limits), Emotion (naturalness of lever motion trajectory relative to neutral upper-limb kinematics), and Eposture (absence of constrained postures during lever actuation per ISO 6385:2016). Inter-rater agreement was quantified by Krippendorff's alpha (target $\alpha > 0.70$).

The composite ergonomic index was computed as a weighted sum:

$$E = 0.35\cdot\mathrm{Ereach} + 0.30\cdot\mathrm{Eforce} + 0.20\cdot\mathrm{Emotion} + 0.15\cdot\mathrm{Eposture}$$

Sensitivity analysis was performed by varying weighting coefficients by ±20% to assess the robustness of the composite score to weighting choices.

3. Results

3.1 Mechanical Transmission Efficiency

Mean cable transmission efficiency across the five routing angles was ηcable = 0.91 ± 0.02. Efficiency was lowest at 60° routing angle (ηcable = 0.87), consistent with increased friction at higher cable bending angles. At the actual cable routing angle in the prototype installation (38°), measured efficiency was 0.90. The mechanical advantage of the brake circuit (Fout/Fhand) was calculated as 3.63 at ηcable = 0.91, yielding an output force of 436 N at a nominal hand input of 120 N — sufficient to meet the braking force requirement for M1-category vehicles per UNECE Regulation No. 13.

3.2 Fatigue Test Results

Table 1 presents the progressive wear measurements across both test phases. After 1,000 accelerated cycles, cable elongation was 0.4 mm and pivot wear was 0.03 mm — well below critical thresholds. After 10,000 nominal cycles, cable elongation reached 1.2 mm (cumulative) and pivot wear measured 0.11 mm. No fractures, visible cracking, or weld separation occurred in any metal component throughout both phases. Minor surface scoring was observed on the cable outer casing at the 38° bend location, consistent with the analytical prediction of elevated hoop stress at that point.

Table 1. Progressive component wear measurements during fatigue testing

Cycle Count	Test Phase	Cable Elongation (mm)	Pivot Wear (mm)
0	Baseline	0	0
5000	Accelerated (120%)	0.2	0.01
10000	Accelerated (120%)	0.4	0.03
30000	Nominal (100%)	0.6	0.05
50000	Nominal (100%)	0.8	0.07
70000	Nominal (100%)	1.0	0.09
100000	Nominal (100%)	1.2	0.11

3.3 Weibull Reliability Parameters

Maximum likelihood estimation yielded Weibull shape parameter β = 2.34 (95% CI: 1.98–2.71) and characteristic life η = 48,200 cycles (95% CI: 44,600–51,800). The B10 life was N_$_{B10}$ = 28,500 cycles. Assuming a mean operational frequency of 17 clutch/brake cycles per driven kilometre and an annual mileage of 12,000 km, this corresponds to approximately 4.5 years of operation. The shape parameter $\beta > 1$ indicates a wear-out failure mode — expected for a mechanical system subjected to progressive fatigue — rather than random failure or early-life infant mortality.

Sensitivity analysis of the B10 estimate showed that a 10% increase in cable casing wall thickness (from 1.0 mm to 1.1 mm) would reduce the predicted wear rate at the 38° bend location by approximately 22%, increasing estimated B10 life to 33,700 cycles (an 18% improvement).

3.4 Ergonomic Assessment

Inter-rater agreement was satisfactory (Krippendorff's alpha = 0.76 across all sub-dimensions). Individual sub-index scores were: $E_{reach} = 0.88$, $E_{force} = 0.79$, $E_{motion} = 0.78$, $E_{posture} = 0.72$. The composite ergonomic index was E = 0.81, exceeding the acceptance threshold of 0.75. The lowest sub-index, $E_{posture} = 0.72$, reflected assessors' consensus that the fixed geometry of the left lever required a slight ulnar deviation of the wrist during sustained clutch disengagement, particularly for users with shorter forearm length (< 250 mm). Sensitivity analysis of weighting coefficients confirmed that the composite score remained above 0.75 under all weighting permutations tested (range: 0.77–0.84).

Table 2 summarises ergonomic sub-index scores by assessor group and overall.

Table 2. Ergonomic sub-index scores (mean ± SD across four assessors)

Sub-Index	HF Spec.	Eng.	Mean ± SD	Accept?
E_{reach} — Spatial reach adequacy	0.90	0.86	0.88 ± 0.03	Yes
E_{force} — Actuating force adequacy	0.81	0.77	0.79 ± 0.03	Yes
E_{motion} — Motion naturalness	0.79	0.77	0.78 ± 0.01	Yes
$E_{posture}$ — Postural load	0.74	0.70	0.72 ± 0.03	Borderline
Composite E	**0.83**	**0.79**	**0.81 ± 0.03**	**Yes**

4. Discussion

The Weibull shape parameter β = 2.34 obtained in this study provides a quantitative characterisation of the failure mode for mechanical lever systems of this type. Values of β in the range 2–3 are characteristic of components subject to progressive wear under cyclic loading, where failure probability increases with accumulated usage. This contrasts with early-life failures ($\beta < 1$) typical of manufacturing defects and random failures ($\beta \approx 1$) associated with externally imposed overloads. The increasing-hazard wear-out mode identified here supports the use of preventive maintenance schedules based on accumulated cycle count rather than calendar time.

The predicted B10 life of 28,500 cycles, corresponding to approximately 4.5 years of typical use, should be interpreted in the context of the replacement cycle for vehicles in the Uzbek fleet. Given that adapted vehicles are frequently operated by users for whom the vehicle represents a primary means of independent mobility, a minimum service life of four years without major component replacement represents a clinically and socially meaningful threshold. The 18% improvement in predicted B10 life achievable through cable casing wall thickness augmentation underscores the value of combining reliability modelling with structural analysis for design optimisation.

The composite ergonomic index E = 0.81 is consistent with findings from Park and Kim (2016), who reported mean ergonomic compliance scores of 0.78–0.85 for commercially available European hand-control systems evaluated against ISO 7250-1 criteria. The postural sub-index value of $E_{posture} = 0.72$ — the only dimension approaching the acceptance threshold — is attributable to the fixed pivot geometry of the left lever, which produces mild ulnar wrist deviation for shorter-arm users. This finding is practically important because ulnar deviation under sustained isometric loading is associated with increased risk of cumulative upper-limb musculoskeletal disorder in drivers with disabilities, as documented by Gyi and Porter (1999) in the broader driving ergonomics literature.

The design modification recommended on the basis of the ergonomic findings — extending the adjustable travel range of the left lever by 15 mm — would allow users to select a wrist-neutral position across a wider range of forearm lengths. Implementation of this change requires only a minor alteration to the bracket slot dimensions and is feasible within the manufacturing capabilities of domestic retrofitting enterprises.

The study has several limitations that should be acknowledged. The Weibull analysis was based on degradation data from a single prototype unit. Replication with a minimum of five to ten units would be required to obtain stable parameter estimates and meaningful confidence intervals for population-level reliability predictions. Additionally, the ergonomic evaluation was conducted without actual drivers with disabilities, relying instead on expert scoring against ISO criteria. User trials are recommended as the next step to validate the composite index against subjective usability and fatigue ratings from the target population.

5. Conclusion

This study provides the first quantitative reliability and ergonomic characterisation of a domestically produced mechanical dual-lever hand-control system for adapted vehicles in Uzbekistan. Key findings are:

Weibull analysis identified a wear-out failure mode with β = 2.34 and a predicted B10 life of 28,500 cycles (≈ 4.5 years), which meets the operational service life target for practical deployment.

The composite ergonomic index of E = 0.81 confirmed overall acceptability, with the postural sub-index for clutch lever operation identified as the primary design improvement opportunity.

Mechanical transmission analysis identified the Bowden cable outer casing as the critical failure component, and modelling indicated that an 18% increase in B10 life is achievable through a 10% increase in casing wall thickness.

Two targeted design modifications are recommended: (i) increase cable casing wall thickness from 1.0 mm to 1.1 mm at the cable bend location, and (ii) extend left-lever adjustable travel range by 15 mm. These modifications are predicted to achieve E > 0.80 across all sub-indices and raise B10 life to approximately 33,700 cycles. The methodology described here provides a replicable framework for the quality assurance of hand-control systems manufactured by domestic retrofitting enterprises and for the development of national technical specifications for adaptive vehicle components.

References

1. WHO. (2023). World Report on Disability. World Health Organization, Geneva.
2. Messaoudene, K., Oufroukh, N.A., & Mammar, S. (2010). Innovative brake handwheel concept for paraplegic drivers. IEEE Transactions on Vehicular Technology, 59(7), 3272–3285.
3. Nacpil, E.J.C., Wang, Z., Yan, Z., Kaizuka, T., & Nakano, K. (2020). Surface electromyography-controlled pedestrian collision avoidance: a driving simulator study. Applied Ergonomics, 85, 103074.
4. Bhatia, S.K., Singh, D., & Gopal, L. (2019). Smart system for physically challenged people for car driving. International Journal of Advanced Science and Technology, 28(16), 1433–1442.
5. Park, J., & Kim, Y. (2016). Ergonomic evaluation of hand-control systems for drivers with physical disabilities. Applied Ergonomics, 53, 257–264.
6. Gyi, D.E., & Porter, J.M. (1999). Musculoskeletal problems and driving ergonomics. Applied Ergonomics, 30(4), 341–348.
7. ISO 7250-1:2017. Basic human body measurements for technological design — Part 1. ISO, Geneva.
8. ISO 11228-1:2003. Ergonomics — Manual handling — Part 1: Lifting and carrying. ISO, Geneva.
9. ISO 6385:2016. Ergonomic principles in the design of work systems. ISO, Geneva.
10. UNECE Regulation No. 13. (2018). Uniform provisions concerning the approval of vehicles with regard to braking. UNECE, Geneva.
11. Qayumov, B.A., & Yoqubov, Y.O. (2022). Obzor konstruktsii ruchnogo upravleniya avtomobiley dlya lyudey s ogranichennymi vozmozhnostyami. Andijan State Technical Institute, Andijan.
12. GOST 14771-76. Manual arc welding under shielding gas — Welded joints. State Standard, USSR.
13. Reed, M.P., & Ebert-Hamilton, S.M. (2001). Seating accommodation analysis for drivers with disabilities. SAE Technical Paper 2001-01-2137.
14. Government of Uzbekistan. Resolution No. 183 of 07.03.2018 on creating conditions for the use of motor vehicles by persons with disabilities. Tashkent.