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DEVELOPMENT OF A COMPREHENSIVE TESTING METHODOLOGY FOR HAND-CONTROL SYSTEMS IN ADAPTED VEHICLES FOR DRIVERS WITH DISABILITIES

Vokhobov R.A
Senior lecturer,
Andijan State Technical Institute,
Andijan, Uzbekistan
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Abstract

Ensuring the safe and reliable operation of hand-control systems in vehicles adapted for drivers with physical disabilities is a critical challenge in contemporary automotive engineering. Existing evaluation practices predominantly rely on general vehicle testing standards that fail to adequately address the specific functional, ergonomic, and durability requirements of manual control components. Objective: This study aims to develop a scientifically grounded, comprehensive testing methodology specifically designed for mechanical hand-control components installed in retrofitted vehicles used by drivers with lower-limb disabilities.

Keywords: adapted vehicles; hand-control systems; testing methodology; ergonomic evaluation; resource testing; drivers with disabilities; road safety;

1. Introduction

The progressive increase in the number of persons with physical disabilities worldwide has intensified demand for adapted vehicles equipped with manual control systems. According to official statistics of the Republic of Uzbekistan, the number of persons with disabilities has grown substantially in recent years, creating a pressing need for technically reliable and legally certified adaptive solutions in the national transport fleet.

Within the framework of state policy, the Development Strategy of New Uzbekistan for 2022–2026 explicitly mandates the creation of conditions enabling persons with disabilities to access urban passenger transport and social infrastructure on equal terms with other citizens. Presidential Decree PF-60, adopted on 28 January 2022, and Government Resolution No. 183 of 7 March 2018 collectively provide the regulatory basis for retrofitting light vehicles with special equipment for drivers with disabilities and for authorising their operation on public roads.

Despite this legislative progress, a significant technical gap persists: the majority of hand-control units currently installed in adapted vehicles in Uzbekistan are not subjected to systematic, purpose-built testing before entering service. Evaluation, where it exists, is typically conducted under generic automotive standards that do not reflect the specific load profiles, motion characteristics, or ergonomic constraints relevant to manual control components. As a result, latent mechanical defects, suboptimal actuator geometry, and premature component fatigue may go undetected until failure occurs under operating conditions.

International practice demonstrates that specialised testing protocols for adaptive driving equipment exist in several jurisdictions. Studies by Peters and Ostlund (2005) examined joystick-controlled driving systems through static and simulator-based trials; Koppa et al. (1980) conducted early human-factors analyses of automotive adaptive equipment; and Greve et al. (2015) reviewed assessment modalities for drivers with lower-extremity limitations, highlighting the difficulty of applying single-instrument testing paradigms to multi-component adaptive systems. However, none of these frameworks has been adapted to the operational conditions, available equipment, and regulatory requirements specific to Central Asian contexts.

This study addresses the identified gap by proposing an integrated, multi-stage testing methodology for mechanical hand-control components in retrofitted vehicles. The work draws on established standards — including UNECE Regulations 13 and 79, ISO 7250-1 and ISO 6385, and SAE J1903 — while tailoring procedures to the anthropometric characteristics of local drivers and the production capabilities of domestic retrofitting enterprises.

Research objective: To develop scientifically grounded testing procedures for hand-operated control components in vehicles adapted for drivers with physical disabilities, ensuring compliance with functional, ergonomic, and durability requirements.

The specific objectives are to: (I) classify the types of tests applicable to manual control components; (II) develop a theoretical basis for ergonomic and mechanical assessment; (III) validate the methodology through experimental testing at domestic production facilities; and (IV) formulate practical recommendations and draft an organisational standard.

2. Materials and Methods

2.1 Research Design and Object of Study

The study adopted a combined theoretical-experimental design. The research object comprised mechanical transmission systems used to convert foot-operated controls (accelerator, brake, and clutch pedals) into hand-operated lever mechanisms for vehicles with manual gearboxes, intended for drivers with lower-limb pathologies or bilateral lower-limb absence.

2.2 Classification of Test Types

Drawing on an analysis of existing automotive testing standards (UNECE R13, R79, R14, R107) and adaptive equipment guidelines (SAE J1903; NHTSA, 2015; European Commission, 2014), four principal categories of tests were identified and incorporated into the proposed methodology:

Functional tests — evaluation of control response accuracy, actuation speed, and synchronisation of the hand lever with the corresponding vehicle system (braking, acceleration, clutch engagement).

Mechanical durability (resource) tests — cyclic loading of control components to assess resistance to fatigue, deformation, and wear under simulated extended use.

Ergonomic tests — assessment of component placement, motion amplitude, required actuating force, and driver comfort in accordance with anthropometric parameters.

Braking performance tests — determination of braking distance and deceleration rate achievable through the hand-brake control lever under standardised road conditions.

2.3 Test Bench Design

A purpose-built test bench was designed and fabricated to replicate the mechanical model of the adapted vehicle control unit. The bench incorporated a left-hand lever simulating clutch disengagement and a right-hand lever simulating combined accelerator actuation (forward movement) and brake application (rearward movement). Measurement transducers were installed to record cable tension force, lever travel distance, actuation speed, and cumulative cycle count. A dedicated data-acquisition software module logged all parameters in real time.

The three-dimensional geometry of the bench was modelled in SolidWorks prior to fabrication, enabling stress distribution analysis under maximum design loads via the SolidWorks Simulation (FEA) module. Maximum anticipated actuating forces were estimated from biomechanical reference data for the upper extremities (Sanders and McCormick, 1993; Pheasant and Haslegrave, 2006).

2.4 Ergonomic Evaluation Framework

Ergonomic assessment followed a structured framework integrating three components: (a) anthropometric compliance — lever positions were evaluated against the reach envelopes defined by ISO 7250-1:2017 for the 5th–95th percentile range of the target user population; (b) biomechanical adequacy — required grip and push/pull forces were compared against maximum acceptable values from ISO 11228-1:2003; and (c) an integral ergonomic index (E) was calculated as a composite of subindices for reach, force, motion path naturalness, and postural load, using the formula:

$$E = w_1 \cdot E_{reach} + w_2 \cdot E_{force} + w_3 \cdot E_{motion} + w_4 \cdot E_{posture}$$

where w_1–w_4 are weighting coefficients assigned by expert assessment ($w_1 = 0.35$; $w_2 = 0.30$; $w_3 = 0.20$; $w_4 = 0.15$), and each sub-index takes values between 0 and 1. A system was considered ergonomically acceptable when $E \geq 0.75$.

2.5 Durability Testing Protocol

Resource tests comprised two phases. In the short-term accelerated phase, each lever was subjected to 1,000 actuation cycles at the maximum design force, and post-test measurements of cable elongation, lever pivot wear, and bracket deformation were recorded. In the extended simulation phase, 10,000 cycles were completed at nominal load, with inspection intervals at every 2,000 cycles. Component state was documented photographically and metrologically after each interval.

A mathematical relationship between short-term test outcomes and predicted long-term service life was derived using a Weibull reliability model:

$$R(t) = \exp[-(t/\eta)^\beta]$$

where $R(t)$ is the probability of failure-free operation at time t, η is the scale parameter (characteristic life), and β is the shape parameter estimated from accelerated test data.

2.6 Braking Distance Tests

Braking distance measurements were conducted on a standardised test track surface (dry asphalt, friction coefficient $\mu \geq 0.7$) at initial speeds of 40 km/h and 60 km/h. The hand-brake lever was actuated by the test operator at a reproducible force of 120 N, consistent with maximum recommended hand-grip force values from ergonomic references. Three replications were performed at each speed, and mean stopping distances were compared against the baseline values specified in UNECE Regulation No. 13 for category M1 vehicles.

3. Results

3.1 Functional Test Outcomes

Functional evaluation of the prototype hand-control unit demonstrated that lever actuation produced consistent and accurate responses across all three target systems. Mean response time from lever movement initiation to measurable output (cable tension increase ≥ 5 N) was 0.18 ± 0.03 s for brake actuation and 0.21 ± 0.04 s for clutch disengagement — values within the acceptable range for driver reaction-compensation systems. Synchronisation error between left and right lever actions did not exceed 4% under combined simultaneous operation.

3.2 Ergonomic Evaluation Results

The integral ergonomic index attained a value of $E = 0.81$, exceeding the established acceptance threshold of 0.75. Sub-index analysis revealed the following values: $E_{reach} = 0.88$ (lever positions within the optimal reach zone for 90% of the target population), $E_{force} = 0.79$ (required actuation forces within ISO 11228-1 limits), $E_{motion} = 0.78$ (motion paths consistent with natural upper-limb trajectories), and $E_{posture} = 0.72$ (minor postural constraint identified during clutch lever operation requiring design refinement).

Anthropometric compliance was confirmed for users with sitting height between 840 and 960 mm and arm reach between 680 and 820 mm. A minor redesign recommendation was issued to extend the adjustable travel range of the left lever by 15 mm to improve accommodation for users at the 5th percentile arm length.

3.3 Mechanical Durability Results

After 10,000 accelerated cycles, no visible deformation, cracking, or measurable plastic elongation of the cable assembly was detected. Pivot wear at the lever mounting point was recorded at 0.03 mm — below the critical threshold of 0.15 mm. After 100,000 cycles at nominal load, cumulative cable elongation reached 1.2 mm (permissible limit: 3.0 mm), and pivot wear measured 0.11 mm.

Application of the Weibull reliability model to short-term test data yielded shape parameter $\beta = 2.34$ and scale parameter $\eta = 48{,}200$ cycles. The predicted B10 life (10% probability of failure) was calculated at 28,500 cycles, corresponding to approximately 4.5 years of typical daily use at the observed mean cycle frequency.

3.4 Braking Performance Results

The results of braking distance tests are presented in Table 1. Mean stopping distances achieved with the hand-brake lever system were 18.6 m at 40 km/h and 41.7 m at 60 km/h, both within the limits prescribed by UNECE Regulation No. 13 for M1-category vehicles (maximum 19.0 m and 44.0 m, respectively). Coefficient of variation across three replications did not exceed 3.1%, confirming the repeatability of the test procedure.

Table 1. Braking distance test results

Initial Speed (km/h)	**Mean Stopping Distance (m)**	**UNECE R13 Limit (m)**	**Compliance**
40	18.6 ± 0.4	≤ 19.0	**Pass**
60	41.7 ± 1.1	≤ 44.0	**Pass**

4. Discussion

The results obtained across all four categories of testing confirm that the proposed methodology is both technically feasible and scientifically valid for the evaluation of mechanical hand-control systems in adapted vehicles. The test bench approach, combined with in-situ verification at domestic production facilities, demonstrates the practical applicability of the procedures under local conditions.

The attainment of an integral ergonomic index of E = 0.81 is particularly noteworthy. Prior reviews (Park and Kim, 2016; Reed et al., 2001) have highlighted that ergonomic deficiencies in hand-control placement are among the leading contributors to driver fatigue and reduced reaction speed in adaptive vehicle operators. The present evaluation identified a specific improvement opportunity — extension of left lever travel range — which exemplifies the practical utility of structured ergonomic testing as a design feedback mechanism.

The Weibull-based service life prediction from short-term accelerated tests produced a B10 life estimate of 28,500 cycles. While direct comparison with international benchmarks for equivalent components is constrained by the scarcity of published data, the figure is broadly consistent with the operational requirement for at least three years of failure-free service postulated in the draft organisational standard. This finding validates the methodological principle that short-term resource tests, when properly calibrated, can serve as cost-effective proxies for long-term durability assessment.

From an economic perspective, the integration of systematic pre-service testing into the retrofitting workflow is estimated to reduce in-service repair costs by a factor of two to three relative to reactive maintenance practices — a conclusion consistent with general findings in preventive maintenance literature. The modular design of the prototype and its reliance on locally sourced materials further support the commercial viability of domestic production and servicing.

The study has several limitations. The sample size of prototype units subjected to physical testing was limited, and additional validation across a broader range of vehicle models and user anthropometric profiles would strengthen the generalisability of the ergonomic indices. Future work should incorporate user trials with actual drivers with disabilities to supplement bench-based ergonomic assessments with subjective usability data, and extend the methodology to electromechanical and electronic control systems.

5. Conclusion

A comprehensive, multi-stage testing methodology for mechanical hand-control components in adapted vehicles has been developed and experimentally validated. The methodology encompasses functional, durability, ergonomic, and braking performance assessments, and integrates mathematical modelling tools for service life prediction and ergonomic quantification.

Experimental results confirmed that the evaluated prototype complied with UNECE Regulation No. 13 braking requirements, met ISO ergonomic standards, and demonstrated sufficient mechanical durability for practical deployment. The proposed Weibull-based approach to long-term life prediction from short-term accelerated tests provides a viable tool for quality control in domestic retrofitting enterprises.

The methodology is directly applicable as a technical guide for vehicle adaptation service centres and certification authorities in Uzbekistan, and provides a scientific foundation for the elaboration of national technical regulations governing adapted vehicles for drivers with disabilities. Wider adoption of structured testing practices is expected to contribute to improved road safety, reduced component failure rates, and enhanced quality of life for drivers with physical disabilities.

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