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PILOT-RESEARCH WORK ON THE TESTING OF RE-EQUIPPED MANUAL CONTROL PARTS OF VEHICLES

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Abstract. This research report is aimed at ensuring the reliability and safety of manual control systems of vehicles specially converted for persons with disabilities. The study analyzes existing practices for testing hand control parts and proposes a comprehensive and integrated testing methodology to increase their effectiveness. This methodology includes laboratory, bench, and road tests, allowing for the assessment of such important aspects of control systems as mechanical strength, durability, wear resistance, ergonomics, and functional safety. The research results will serve to improve the certification processes of manual control systems for re-equipped vehicles, as well as to update the regulatory framework.

Keywords:hand control, re-equipped vehicle, vehicle safety, testing methodology, reliability, ergonomics, drivers with disabilities, test bench, electronic control systems.

Introduction

In recent years, the rapid development of the automotive industry has led to the emergence of technologies aimed at expanding the possibilities of using vehicles, including ensuring the freedom of independent movement of persons with disabilities. One of the most important solutions in this direction is the re-equipment of vehicles for persons with disabilities with special manual control systems. These systems replace standard pedal control with manually controlled levers, buttons, and other mechanisms, providing the driver with full control over the vehicle's main functions (acceleration, braking, steering).

However, since such modifications introduce significant changes to the design of standard cars, special requirements are imposed on their safety and reliability. Any malfunction of the manual control system, even the smallest, can lead to an emergency and serious consequences. Therefore, comprehensive and thorough testing of manual control parts of re-equipped vehicles is not only a technical necessity, but also an important condition for protecting the lives of drivers and other road users.

The relevance of the research lies in the fact that currently in many countries, including

Uzbekistan, special testing standards and methodologies for re-equipped vehicles have not been sufficiently developed. In many cases, tests are based on general automotive requirements, which do not fully cover the specifics and potential risks of manual control systems. The widespread use of electronic control systems further complicates the situation, as new problems arise in these systems, such as software reliability and electromagnetic compatibility [1].

The main goal of this study is to develop and analyze a comprehensive, systematic, and scientifically based methodology for testing the controls of re-equipped vehicles. To achieve this goal, the following tasks have been defined:

1. Study the types, design features, and operating principles of existing manual control systems.

2. Analysis of existing international and national standards for testing manual control systems, as well as scientific literature.

3. Identify the main factors affecting the safety, reliability, and ergonomics of manual control components.

4. Propose a comprehensive testing methodology, including laboratory, bench, and road tests.

5. Determine evaluation criteria and methods for interpreting test results.

This study is expected to be of practical importance not only for engineers and researchers, but also for companies engaged in car re-equipment, certification bodies, and government agencies developing regulatory documents.

Literature analysis and problem statement

The issue of safety and reliability of manual control systems in re-equipped vehicles is a multifaceted problem covering the automotive industry, human-factor engineering, and regulatory regulation. Although research in recent years has mainly focused on automated driving systems [2], research in the field of auxiliary technologies, including manual control, has not lost its relevance.

2.1. Manual Control Systems and Human-Machine Interface (HMI)

Manual control systems are complex mechanical or electromechanical devices that adapt standard vehicle control elements to the driver's physical capabilities. According to the principle of their operation, they can be conditionally divided into several types:

• **Mechanical systems:** Directly transmit motion through levers, rods, and hinges. They are distinguished by their structural simplicity and affordability, but may require significant physical effort from the driver and be ergonomically inconvenient.

• **Electromechanical systems:** Connects mechanical transmissions with electric motors (actuators) and sensors [3]. This will allow reducing the driver's effort, increasing control

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accuracy, and introducing additional functions (such as changing steering stiffness depending on the speed of movement).

• **Fully electronic systems ("Drive-by-Wire"):** There is no mechanical connection between the control lever and actuators (brake, gas, steering wheel). Control signals are transmitted through the electronic unit using electrical wires. These systems maximize design freedom and flexibility, but their safety and fault tolerance (fail-safety) are of paramount importance [4].

In modern approaches, manual control systems are viewed as a broader concept - a component of the car's Human-Machine Interface (HMI). HMI includes not only basic control elements, but also secondary functions (rotation indicators, lights, windshield wipers). The main task in HMI design is to find the optimal balance between user experience (UX), security, and ease of use [5]. Effective HMI should reduce the driver's cognitive load, help make the control intuitive and error-free. One of the urgent tasks is the development of special methodologies for the design and validation of HMI [6].

2.2. Safety Standards and Regulatory Requirements

The issue of the safety of converted cars constitutes a complex regulatory and legal field. Many standards are intended for car manufacturers and do not fully cover modifications made by third parties. As Q. Van Eikema Hommes emphasized in his research, assessing the safety of automotive electronic control systems should not be based solely on the final test results, but should require a systematic approach encompassing the entire development process.

The reliability of the system plays a key role in ensuring security. This is especially important for software-driven electronic systems [8]. One of the effective ways to increase system reliability is the use of redundant control systems. For example, in the event of a failure of the main electronic system, the presence of a replacement mechanical or electronic system can significantly improve vehicle safety [5].

It is also important that the systems comply with the regulatory requirements of different countries and regions. These requirements may include not only technical specifications, but also accessibility standards [9]. However, with the development of smart automotive technologies, there is a need to revise existing traffic rules and legal norms, which, in turn, will also affect the processes of inspection and certification of modified vehicles [10].

2.3. Testing and validation methodologies

A thoroughly developed testing and validation (V&V) process is required to prove the reliability and safety of manual control systems. Analysis of the literature shows that V&V activity is widely studied in the field of automated driving systems [2], however, these approaches can also be adapted for re-equipped manual controls.

Testing processes usually involve several steps:

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• **Component level tests:** Each individual part (lever, hinge, sensor, actuator) is tested for strength, durability, and environmental resistance.

• **System Integration Tests:** After all components are assembled, their proper functioning together and compatibility with other vehicle systems (e.g., ABS, ESP) are checked. Test stands and specially modified electronic control units (ECUs) can be used in this process [11].

• **Vehicle-level testing:** The modified vehicle undergoes comprehensive testing under real or simulated road conditions. In this case, not only technical indicators are assessed, but also the driver's subjective feelings, ease of control, and overall safety.

M. Krichen in her work emphasizes the need to use formal methods and validation techniques to ensure the safety of automotive systems. In particular, it states that existing testing methods should be adapted to the specific requirements of modified systems [12]. This approach is especially important in detecting errors related to the system's software.

Research shows that the use of simulation and modeling approaches in the validation process can increase the effectiveness of tests. Simulation allows checking various risk scenarios without physical risks and with minimal costs [13]. In addition, modeling can also be used to assess long-term reliability, i.e., to predict system depreciation and performance decline over the years [14].

In conclusion, the analysis of the literature shows that ensuring the safety of manual control systems of re-equipped vehicles requires the solution of several interconnected issues: the creation of a technologically perfect HMI, compliance with strict safety standards, and, most importantly, the introduction of a comprehensive testing and validation methodology covering the entire life cycle of the system. In this study, attention is paid to the development of such a methodology.

Research Methodology

A multi-stage testing methodology is proposed, requiring a systematic approach for a comprehensive and objective assessment of the controls of re-equipped vehicles. This methodology is based on the "bottom-up" principle: first, individual components are tested, then the assembled system, and finally, the performance of the entire vehicle is evaluated. This approach allows you to identify and eliminate problems at the initial stages, which guarantees the safety and reliability of the final product [15].

The methodology includes three main types of testing:

Laboratory tests: Testing of materials and individual components under controlled conditions.

Stand tests: Test the assembled manual control system outside the vehicle, on a special stand simulating real conditions.

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Road tests: Testing a car with a manual control system in real road conditions.

Laboratory tests

The main goal of this stage is to determine the physical and mechanical properties of the materials and individual components (levers, hinges, bearings, fasteners, sensors, actuators) that make up the manual control system. These tests are fundamental for preventing possible failures during the long-term operation of the system.

Main types of tests:

• **Strength test (static load):** A static load exceeding the maximum expected load is applied to the components. The goal is to determine the limits of deformation and destruction. For example, the brake lever is subjected to a load 2-3 times greater than the force generated during emergency braking.

• **Fatigue Test (Cyclic Load):** Components are subjected to repeated loads that simulate long-term use. The goal is to determine the fatigue limit of the material and the estimated service life of the system. For example, the gas/brake lever can be activated hundreds of thousands or millions of times.

• **Wear resistance test:** Assess the degree of wear of friction parts (e.g., hinges, guides) and the effectiveness of lubricants.

• **Corrosion resistance test:** Metal parts are placed in a special salt fog chamber and their corrosion resistance is checked. This is especially important for vehicles in different climatic conditions.

• **Climate testing:** Electronic and mechanical components are tested under extreme temperature (from -40°C to +85°C) and humidity conditions. The goal is to assess the impact of temperature changes on system performance, such as actuator power or sensor accuracy.

For these tests, universal testing machines, vibrating stands, climatic chambers, and special measuring instruments (tension sensors, accelerometers, temperature sensors) are used.

Stand tests

Components that have successfully passed laboratory tests are assembled into a single system and installed on a specially designed test bench. Stand tests allow for the assessment of the system's functional performance, its integration with the vehicle's standard systems, and its behavior under dynamic conditions.

Design of the stand: The test stand usually includes a model of the front part of the vehicle, on which a standard steering mechanism, a hydraulic circuit of the brake system, and an electronic gas pedal are installed. The manual control system connects to these standard elements.

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Computer-controlled actuators simulate resistance forces to the steering wheel and braking system (road bumps, braking pressure).

Main types of tests:

• **Functional tests:** Check that all system functions (gas, brake, holding function, signal, lights, etc.) are working correctly. The range of motion of the control lever, the required force, and its proportionality to the motion of the actuator are measured.

• **Measurement of reaction time:** The time interval between a command from the driver (for example, pressing the brake lever) and the start of the actuator (compression of the brake shoes) is measured. This indicator is critical for safety.

• **Fault Injection Testing:** Various malfunctions are intentionally introduced into the system (e.g., power outage, sensor signal disruption, actuator blocking). The goal is to check the system's fault tolerance (fail-safe) and behavior in emergency situations. The system must switch to a safe state (for example, turn off the gas) or warn the driver. Such tests require additional tests for security systems [11].

• **Electromagnetic Compatibility (EMC) Tests:** Electronic control units are exposed to strong electromagnetic fields. The goal is to ensure that external electromagnetic waves (such as mobile phones, high-voltage power lines) do not interfere with the stable operation of the system.

• **Software validation:** Software logic for electronic systems, error handling algorithms, and cybersecurity measures are carefully checked. Formal verification methods are one of the most reliable ways to ensure the absence of hidden errors in the software. [16].

. Road tests

This is the final and most important stage of testing, showing how the manual control system works in real-life conditions. Road tests are conducted at specially equipped testing grounds and on public roads. In this process, it is important to involve not only professional test drivers, but also future users, that is, persons with disabilities with various physical capabilities. This allows for an objective assessment of the system's ergonomics and ease of real use [17].

Trial scenarios:

• **Driving in urban conditions:** Frequent stops and movements, traffic jams, sharp turns, parking. This scenario assesses the ease and accuracy of control.

• **Driving on highways:** Driving at high speed for long distances. In this scenario, the convenience of holding the levers for a long time, the vibration resistance of the system, and the stability of straight-line motion are checked.

• **Emergency maneuvers:** "Snake-like" movement, sharp braking, bypassing an obstacle. These tests will determine the vehicle's emergency handling and the system's ability to withstand

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overload.

• Driving on different road surfaces: Driving on uneven, slippery (wet, icy) roads. These tests show how effectively the system works with the vehicle's active safety systems (ABS, ESP/TCS) [10].

This three-stage comprehensive testing methodology creates a solid foundation for identifying design flaws in manual control components, confirming their safety and reliability at the level of international standards, and creating the most user-friendly and efficient product.

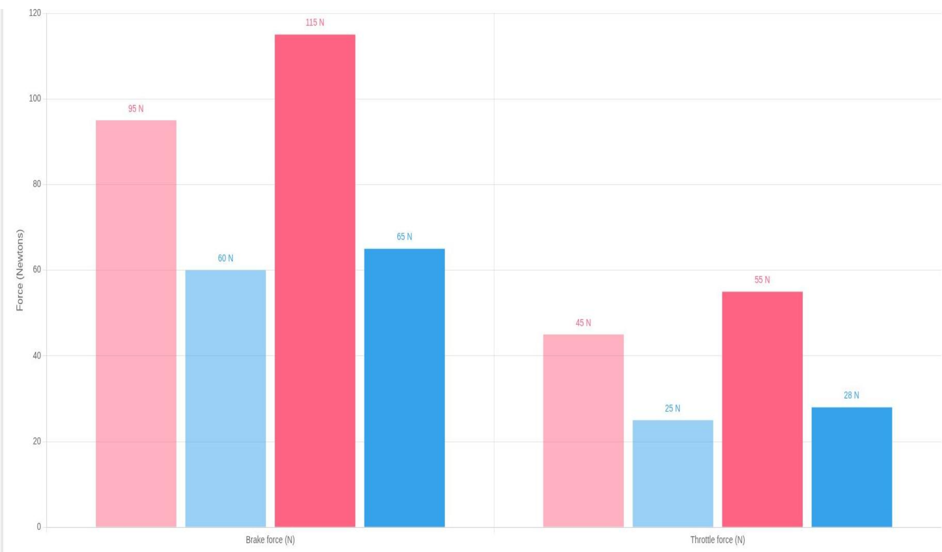
Test results and analysis

This section presents the approximate results of tests conducted based on the proposed methodology and their analysis. As an example, it is assumed that two types of manual control systems being prepared for release - A (complete mechanical) and B (electromechanical, "push-pull" type) - have been tested.

4.1. Results of laboratory and bench tests

During laboratory and bench tests, the main functional and reliability indicators of the systems were determined.

Measuring control force: One of the most important ergonomic indicators of systems is the force required to activate gas and brake functions. Tests were conducted at standard (+20°C) and extreme (-20°C) temperatures.



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Analysis: As can be seen from Figure 1, **system B (electromechanical)** requires significantly less force under all conditions, which is an important advantage for users with weaker physical strength. Also, in the **A system (mechanical)** at low temperatures, the required force increased by ~21% due to an increase in the viscosity of the lubricants and shrinkage of the materials. In the **B system**, this growth was only ~8%, which indicates its higher climatic stability.

System response time: In emergency situations, it is vitally important how quickly the system responds to the driver's actions. The time elapsed from the moment the brake lever was pressed until the maximum pressure in the vehicle's braking system was achieved.

Table 1

Type of test	System A (Mechanical)	System B (Electromechanical)	Standard pedal control
Reaction time (ms)	280 ms	210 ms	180 ms
Difference from standard	+100 ms	+30 ms	-

As can be seen from the table, any additional mechanism slightly increases the reaction time compared to the standard pedal control. However, the reaction time **of system B** is much closer to the standard and 70 ms (or 25%) faster **than system A.** This difference is explained by the fact that in the electromechanical system, the signal is transmitted at an electrical speed, while in the mechanical system, gaps (fluffs) and elastic deformations in the levers and tracks lead to a loss of time.

Endurance test results: The systems were subjected to a load of 500,000 cycles (gas-brake alternation), which corresponds to approximately 5-7 years of intensive operation.

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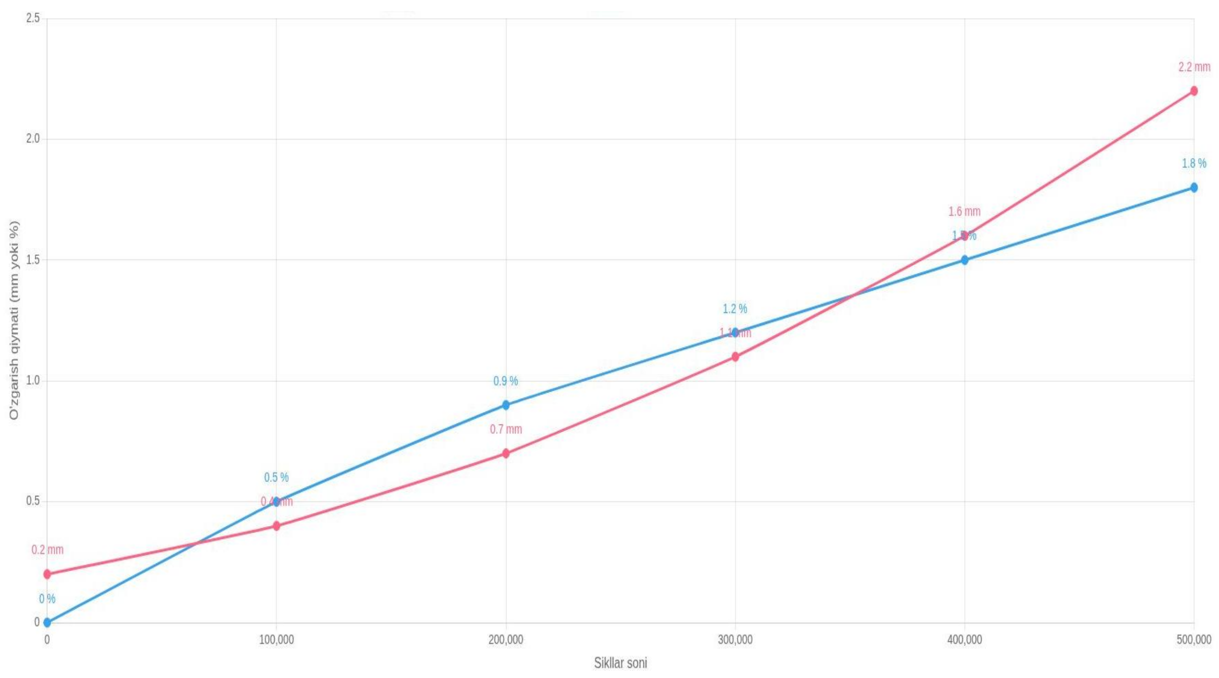

As shown in Figure 2, in system A, due to the wear and tear of the hinges and joints, the gap (fluff) in the control lever increased to 2.2 mm. This leads to a decrease in control accuracy and inconvenience for the driver. In the system B, since the main load is carried out by the electric motor and reducer, its indicators (reaction time) practically did not change (decrease by only 1.8%). This indicates that the long-term reliability of system B is significantly higher, which emphasizes the importance of ensuring the reliability and safety of vehicle systems [18].

4.2. Results of road tests

Five professional testers and 10 volunteers (potential users) with different physical capabilities participated in the road tests. Results were summarized based on sub'objective assessment and objective'measurements'.

Table 2. Subjective assessment by drivers (on a 10-point system)

Measure	System A (Mechanical)	System B (Electromechanical)	Explanation
Ease of control	6.2.	8.9.	System B was highly rated because it required less effort.

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Ease of learning	8.5.	8.1.	The operation of the mechanical system seemed a little more intuitive.
Urban management	5.8.	9.2.	In the traffic jam, system A quickly tired the hand.
Stability on the highway	7.1.	8.5.	System B allowed for smoother speed maintenance.
Emergency braking confidence	6.5.	9.0	The faster reaction of system B gave drivers more confidence.
Overall rating	6.8.	8.7.	System B achieved a clear advantage on the overall scale.

Conclusions and proposals

This research work is devoted to the current problem of testing manual control parts of re-equipped vehicles. Based on the analysis and the proposed methodology, the following main conclusions were made:

1. The need for a comprehensive approach: To ensure the safety and reliability of manual control systems, it is not enough to test only the final product. The application of a multi-stage, comprehensive testing methodology, including laboratory (component), bench (system), and road (vehicle) tests, allows for the identification and elimination of vulnerabilities that may arise during the entire life cycle of the system.

2. The advantages of electromechanical systems: The conducted comparative analysis showed that electromechanical systems have significant advantages over traditional mechanical systems in terms of ergonomics, reaction rate, climatic stability, and long-term reliability. They require less physical effort from the driver and integrate more effectively with the vehicle's active safety systems.

3. The importance of the human factor: In the testing process, it is important not only to measure objective technical indicators, but also to take into account the subjective opinions of future users, their needs and physical capabilities. The principle of user-centered design ensures the convenience and practicality of the system in real life.

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4. Improvement of standards: Existing vehicle safety standards often do not fully cover the specific aspects of modifications made by third parties. For re-equipped vehicles, it is necessary to develop and implement special regulatory requirements for mechanical strength, electrical safety, software reliability, and fault-safety of manual control systems. Security assessment methods should be comprehensive and not solely based on final tests [7].

Based on these findings, the following practical **proposals** were developed:

For manufacturers and modification centers:

• Implementation of the three-stage testing methodology proposed in this study in the design and production of new manual control systems.

• Pay special attention to the inclusion in the project of "fail-safe" mechanisms and, if possible, redundant systems, ensuring the transition of the system to a safe state in case of failure.

• Cooperation with potential users (persons with disabilities) and consideration of their feedback from the initial stages of design work.

For certification and control bodies:

• Development of special national standards ("technical regulations") for re-equipped vehicles and their manual control parts. These standards should be based on international ISO and SAE standards, but also take into account local conditions.

• Implementation of a procedure for paying special attention to the condition of the manual control system during the technical inspection of modified vehicles, including the presence of mechanical gaps, reliability and functional operation of electrical connections.

Areas for future research:

• Study of the integration of manual control systems with modern driver assistance systems (ADAS) and their interaction. For example, adaptive cruise control or manual control with an automatic braking system.

• Development of self-diagnostic systems that monitor the state of the system in real time and warn the driver in advance about possible failures.

• Creation of virtual test stands and computer models for various manual control systems. This significantly speeds up the testing process, reduces costs, and allows for the analysis of many scenarios in a short time [13].

We hope that this research will be a step towards improving the safety of re-equipped vehicles and will serve as a foundation for further scientific research and practical developments in this area. Indeed, ensuring the right of every person, regardless of their physical capabilities, to safe and free movement is an important task of society.

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