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Quality and Reliability Control of Refurbished Automotive Printed Circuit Boards: Evaluation Criteria, Testing Methods, and Impact on Vehicle Safety

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ABSTRACT

Component-level repair of automotive electronic control units is widely used in practice as an alternative to full replacement. However, there is still no clear, consistent way to judge whether such a repair can be considered reliable. Drawing on 210 real repair cases from 2023–2024, this article looks at how refurbished units are actually evaluated, what signals indicate that a repair will hold over time, and why these decisions have direct safety implications for the vehicle. Methods of analysis and synthesis, a structural-functional approach, and a structured in-depth interview with a practicing specialist were employed. It was found that standard testing with power connection and a diagnostic scanner detects only some of the faults: defects in the interconnections between the board layers remain undetected until the unit is subjected to actual load in the vehicle. Eliminating the root cause of the malfunction in the vehicle prior to unit repair and load testing reduces the rate of repeat failures to 5–10%. The proposed multi-layer validation model combines microscopic inspection, electrical measurements, diagnostic scanning, memory verification, and load, thermal, and mechanical stress testing. The results provide a practical basis for developing a standardized quality-control protocol for independent service centers working with safety-critical automotive electronic modules. For active safety systems, where a failure can directly cause an accident, a latent fault is more dangerous than a complete unit failure: it is not detected by the self-diagnostic system but manifests during emergency braking or a sharp maneuver. The study also demonstrates that repair decisions for safety-critical modules should be based not only on functional recovery but also on the predictability of their behavior under dynamic operating conditions.

KEYWORDS

automotive electronics, printed circuit board, quality control, load testing, reliability, engine control unit, functional safety.

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Контроль якості та надійності відновлених автомобільних друкованих плат: критерії оцінки, методи випробувань та вплив на безпеку транспортних засобів

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АНОТАЦІЯ

Ремонт електронних блоків керування автомобілями на рівні компонентів широко використовується на практиці як альтернатива повній заміні. Однак досі немає чіткого та послідовного способу оцінити, чи можна вважати такий ремонт надійним. Спираючись на 210 реальних випадків ремонту з 2023–2024 років, у цій статті розглядається, як насправді оцінюються відновлені блоки, які сигнали вказують на те, що ремонт буде надійним з часом, і чому ці рішення мають прямі наслідки для безпеки транспортного засобу. Були використані методи аналізу та синтезу, структурно-функціональний підхід та структуроване поглиблене інтерв'ю з практикуючим спеціалістом. Було виявлено, що стандартне тестування з підключенням живлення та діагностичним сканером виявляє лише деякі несправності: дефекти у взаємоз'єднаннях між шарами плати залишаються невиявленими, доки блок не піддається фактичному навантаженню в транспортному засобі. Усунення першопричини несправності в транспортному засобі перед ремонтом блоку та навантажувальними випробуваннями знижує рівень повторних відмов до 5–10%. Запропонована багатошарова модель валідації поєднує мікроскопічний огляд, електричні вимірювання, діагностичне сканування, перевірку пам'яті, а також випробування на навантаження, теплові та механічні напруження. Результати забезпечують практичну основу для розробки стандартизованого протоколу контролю якості для незалежних сервісних центрів, що працюють з критично важливими для безпеки автомобільними електронними модулями. Для систем активної безпеки, де відмова може безпосередньо спричинити аварію, прихована несправність є більш небезпечною, ніж повний відмову блоку: вона не виявляється системою самодіагностики, але проявляється під час екстреного гальмування або різкого маневру. Дослідження також демонструє, що рішення щодо ремонту критично важливих для безпеки модулів повинні ґрунтуватися не лише на функціональному відновленні, але й на передбачуваності їхньої поведінки в динамічних умовах експлуатації.

КЛЮЧОВІ СЛОВА

автомобільна електроніка, друкована плата, контроль якості, навантажувальні випробування, надійність, блок керування двигуном, функціональна безпека.

1. Introduction

Component-based repair of automotive electronic control units – where a technician addresses the faulty element directly on the board rather than replacing the entire module – typically costs 20–30% of the price of a new unit [1; 2]. This approach is widely adopted in practice, yet a question central to its safety implications is rarely examined systematically: how reliable will the repaired unit be?

For most vehicle systems, this is an economic issue. For anti-lock braking systems, steering, or airbags, the answer is literally a matter of life and death: failure of these systems can cause an accident. A modern mid-range passenger car can contain up to eighty electronic control units [1], and some of them are specifically responsible for safety. Despite this, there is still a lack of systematic scientific research in the field of quality control for the component repair of automotive printed circuit boards: most existing studies focus either on the manufacturing quality of new products or on computer diagnostics for vehicles.

This article aims to describe what systematic quality control looks like during the restoration of automotive electronic control units and to demonstrate the consequences of its absence. To this end, current international standards in this field have been analyzed, and the author's practical experience has been systematized based on 210 documented repair cases.

2. Literature Review

The reliability of electronic components is a widely studied field. A. Birollini systematized methods for calculating failure probability and described how various degradation mechanisms affect component lifespan [3]. Alongside this, M. Pekt proposed an alternative approach known as "failure physics": instead of generalized statistical curves, he predicts the remaining life of a specific component using physical models of the processes that degrade that particular type of material [4]. The difference is significant: for repaired boards, where re-soldering alters the mechanical properties of the joints, statistics for new products may provide misleading guidelines.

The regulatory framework for the quality of soldered joints is based on IPC standards. The IPC-A-610H standard [5] establishes three quality classes and describes for each of them what constitutes an acceptable soldered joint, including for integrated circuits with under-body contacts that cannot be inspected without special equipment. Automotive electronics fall under the second or third class depending on the unit's function. Repair technology is regulated by the related IPC-7711C/7721C standard [6], which specifies acceptable temperature ranges during rework and methods for verifying results.

The safety of repaired units is addressed by ISO 26262:2018 [7], which classifies automotive systems by potential hazard levels from A to D. For the braking system and steering, the highest level is established, at which the permissible failure probability does not exceed 10^{-8} per hour. The methodological basis for this standard is IEC 61508-1:2010 [8], which covers the functional safety of electronic systems in general. The behavior of soldered joints under the influence of thermal cycles in the engine compartment was investigated by Lall et al., who found that it is precisely cyclic thermal expansion and contraction that most often destroys the contacts of microchips with ball leads [9]. Schnavach and co-authors added an important observation to this: deviations from the standard temperature profile during re-soldering significantly accelerate this process [10]. Protection against static discharge during maintenance is regulated by ANSI/ESD S20.20 [11], and the exchange of diagnostic data between units is regulated by SAE J1979 [12]. Despite the existence of these studies, the quality of the refurbished control unit as a separate subject of study remains an under-researched topic.

3. Problem Statement

Despite established standards for electronic manufacturing and repair, there is no comprehensive approach for assessing the long-term reliability and functional safety of refurbished automotive printed circuit boards after component-level repair.

4. Methods and Materials

The study employed methods of analysis, synthesis, and comparison, a structural-functional approach, as well as a structured in-depth interview with a practicing specialist.

Y. Breusov is a specialist in the component repair of automotive electronic control units. In 2023 and 2024, he repaired 210 units: 80 units in 2023 and 130 in 2024. Engine control units account for the largest share of the work (60%), followed by body control units (20%), passenger safety system units (10%), and transmission control units (10%). The vast majority of repaired units come from European-made vehicles, where the electronics are more complex, and Bosch units are very common. To perform the work, the workshop is equipped with RIGOL MSO5074 and Autel MaxiSys Ultra oscilloscopes, a Siglent SPD3303X-E laboratory power supply with adjustable current limiting, an Autel MaxiIRT thermal imager, a Vevor stereo microscope with 7x to 45x magnification and a YIZHAN 48MP 4K digital microscope, W.E.P 992D and Yigua 1000b soldering stations, a 30-liter Vevor ultrasonic cleaner, Magic Motorsport Flex, Xhorse Multiprog, and Orange 5 programmers, and Komodo and LA104 data bus analyzers.

The interview materials are organized into four categories corresponding to the structure of the article: criteria for evaluating the quality of a refurbished circuit board, testing methods, measures to reduce repeat failures, and the impact of repair quality on vehicle safety. Interview responses were grouped by these categories, and conclusions were drawn from recurring patterns identified across the 210 documented repair cases. The obtained data were compared with the requirements of the IPC-A-610H, ISO 26262, and IEC 61508 standards.

5. Results and Discussion

5.1. Criteria for Evaluating the Functionality of Refurbished Electronic Circuit Boards

Before deciding whether a refurbished circuit board is suitable for installation in a vehicle, it is evaluated based on four complementary criteria.

The evaluation begins with a microscopic examination of the board for mechanical damage, cracks, burn marks, corrosion, and signs of liquid ingress. A 7x magnification is convenient for soldering, as both the component and the soldering iron are visible in the field of view; to detect microdefects, 45x magnification is applied. A practical example illustrates just how important this is. A sensor power supply error kept occurring on one unit, and checking the wiring and measurement circuits yielded no results. Examination of the board under a microscope with side lighting revealed a crack in a ceramic capacitor as wide as a human hair. When the board heated up, the capacitor expanded and shorted the power line to ground, causing the error. Without a microscope, you could search for such a defect for hours and never find it. The IPC-A-610H standard [5] for Class 3 quality does not allow any cracks in solder joints and requires that the solder fill at least three-quarters of the pin height.

Electrical testing complements the visual inspection. The current consumption, voltages on the internal power lines, and the waveforms on the data buses are measured using an oscilloscope. The normal current consumption of the motor control unit in standby mode is 10–20 mA, and exceeding this value indicates a current leak. In one instance, the multimeter showed normal voltage readings on the data bus, while the oscilloscope detected noise that should not be present in a healthy signal. When the voltage on the line is 3.2 V instead of the standard 5 V, this indicates a leak or a damaged chip port. The multimeter will not detect such deviations.

After the electrical measurements, the diagnostic scanner is connected to read the unit's identification data, check for internal errors, and observe how the unit responds to requests. The absence of errors in the scanner does not in itself guarantee anything: the board may communicate normally with the scanner while simultaneously having a defect that only manifests itself under load.

The evaluation concludes with a check of the data stored in the memory chips: the vehicle identification code, anti-theft system keys, and calibration parameters. If this data is lost or damaged after repair, the car will not start. A complete copy of the memory contents is preserved before repair on two separate media; after recording, every bit is verified against the original, and the anti-theft system status is confirmed via scanner live parameters following reinstallation.

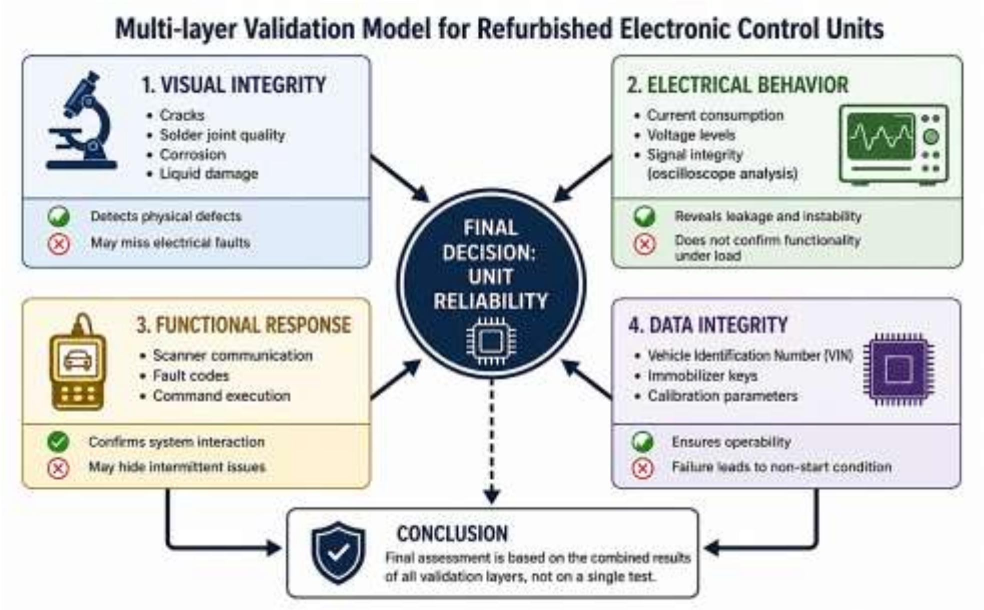

Figure 1. Multi-layer validation model for refurbished electronic control units

Source: Compiled by the author.

5.2. Testing Procedures for Printed Circuit Boards After Repair

The full testing cycle for a refurbished unit takes three to eight hours. It begins with data backup and an initial check: the unit is connected to a laboratory power supply with current limiting and to an oscilloscope, while simultaneously capturing a copy of the memory chip contents. Current limiting is critically important here: if there is a fault in the board, the power supply will simply shut off rather than burn out the traces.

If the board has been in liquid, it is washed in an ultrasonic cleaner. Ultrasonic vibrations create microscopic bubbles in the liquid, which burst and mechanically dislodge dirt and salts from beneath the chip casings, where no brush can reach. Washing is performed at a temperature of forty to fifty degrees Celsius for five to ten minutes: shortening the time reduces effectiveness, while exceeding it can damage soldered joints. After washing, the board is rinsed with isopropyl alcohol and thoroughly dried.

When replacing microchips with under-body contacts, a two-stage heating method is applied in accordance with component-specific temperature profiles. The actual board temperature is monitored by an external thermocouple positioned adjacent to the component, rather than relying on the soldering station's built-in sensor, which reflects nozzle temperature only [9].

After repair, the board is tested on a test bench. A laboratory power supply replaces the battery, a set of cables is connected to the unit's connector, and a signal generator supplies the unit with simulated values from the engine sensors. The test verifies stable current consumption, correct voltage values, and the square-wave shape of the data bus signal.

For a long time, bench testing alone was considered sufficient. Subsequent field experience demonstrated an important limitation: a Mercedes-Benz engine control unit passed all bench tests, but two days later the vehicle stalled in traffic. The cause turned out to be a damaged interlayer junction beneath one of the capacitors.

Under the low load of the test bench, this defect did not manifest itself, but under the actual current of the injectors and solenoid valves, the damaged area heated up, its resistance increased, and the chip's supply voltage dropped below the permissible level.

After that, the testing procedure was changed. Resistors or lamps that roughly correspond to the load of the actual coils and valves are now connected to the unit's outputs, and voltage stability is checked with an oscilloscope while the unit is operating under load. The board is also heated with a heat gun to 80–90 °C to detect cracks that open due to thermal expansion, and tapped with a plastic probe to check for bad contacts.

Before closing the unit, a protective varnish, such as Plastik 70 or urethane, is applied to the board in two layers. The varnish protects against moisture and condensation; without it, corrosion can appear on the board within a month, especially if the unit is located in the lower parts of the body. Contact connectors, programming points, and heat sinks are left open.

Table 1. Post-repair testing protocol for refurbished electronic control units

Stage	Procedure Description	Key Parameters / Conditions	Equipment Used	Failure Indicators	Purpose
Initial setup & data backup	Unit connected to lab power supply with current limiting; full memory dump created	Current limiting enabled; stable power input	Laboratory power supply, memory programmer, oscilloscope	Power shutdown on startup; abnormal current draw	Prevents secondary damage; preserves original data
Cleaning (if liquid exposure)	Ultrasonic cleaning followed by alcohol rinse and drying	40–50°C; 5–10 min; controlled drying	Ultrasonic cleaner, isopropyl alcohol	Residual contamination; corrosion traces	Removes salts and contaminants under components
Component replacement	Microchips replaced using controlled thermal profile	Bottom heating: ~150°C; top: 230–250°C; peak ≤245°C	Hot air station, preheater, thermocouple	Overheating; solder defects; misalignment	Ensures proper soldering without damaging PCB
Bench testing	Simulation of ECU operation without real vehicle load	Stable current; correct voltage; clean signal waveform	Power supply, signal generator, oscilloscope	Signal noise; voltage drop; unstable behavior	Verifies basic functionality
Load simulation testing	Realistic electrical load applied to outputs	Load matching injectors/actuators; voltage stability under load	Resistors / lamps, oscilloscope	Voltage drop under load; overheating	Detects faults not visible in idle conditions
Thermal & mechanical stress test	Heating and physical tapping to reveal hidden defects	80–90°C heating; controlled mechanical impact	Heat gun, probe	Intermittent faults; signal disruption	Identifies cracks and weak connections
Protective coating	Application of protective varnish	Two-layer coating; selective masking	Conformal coating (Plastik 70 / urethane)	Poor coverage; contamination of contacts	Prevents moisture-induced corrosion

Source: Compiled by the author.

5.3. Minimizing Recurring Failures and Technical Risks

Analysis of the causes within this 5–10% reveals the following distribution: approximately 50% of repeat failures occur when the repair itself was performed correctly but the source of excessive load was not eliminated from the vehicle; around 40% result from a new fault in the same circuit due to natural aging of adjacent components; and fewer than 1% are attributable to a hidden defect missed during the repair process. This breakdown underscores that the majority of recurrences are preventable through pre-repair vehicle diagnostics rather than improvements to the repair procedure itself.

One documented case illustrates this pattern clearly. After replacing the power switch in the headlight control unit of a BMW E70 and successfully testing it, the unit was installed in the car, and an hour later the switch failed again. An inspection of the vehicle revealed two causes: damaged headlight wiring insulation, which shorted out when driving over bumps, and a cheap LED bulb that the owner had installed himself and which caused an unacceptable current surge when turned on. Neither of these causes can be detected when testing the unit outside the vehicle. In fact, this is why the unit is generally not accepted for repair without the vehicle: the true cause of the malfunction is more often found in the vehicle itself, rather than in the unit.

Documentation for each repair includes the vehicle identification number, software version, a list of error codes before and after repair, photographs of the circuit board at all stages, and saved memory copies. When a customer returns, the current error codes are compared with the repair log, and it is immediately determined whether this is a warranty case or a new malfunction unrelated to the previous repair.

Static electricity discharge is a risk that is often underestimated. According to the ANSI/ESD S20.20 standard [11], a static discharge may not destroy the microchip instantly, but only damage its structure. Afterward, the unit responds normally to all tests for several weeks, and then suddenly fails for no apparent reason. Preventive measures are simple: a grounding wrist strap, an antistatic mat, and a grounded tool. Dividing the workspace into a diagnostic zone, a disassembly and cleaning zone, a soldering zone, and a storage zone for finished units prevents metal shavings from disassembling enclosures from falling onto exposed circuit boards in the soldering zone. Each warranty return concludes with the addition of a new step to the test protocol, addressing the identified gap.

5.4. The Impact of System Quality Control on Vehicle Safety

The ISO 26262:2018 standard [7] classifies automotive systems by levels of potential hazard ranging from A to D. Anti-lock braking systems, electronic stability control systems, and electric power steering systems fall into the highest levels, C or D, where the permissible failure probability does not exceed 10^{-8} per hour. Repairing such systems carries direct responsibility for the safety of people on the road.

What happens when this responsibility is ignored is illustrated by a Toyota electric power steering unit that arrived for evaluation after being serviced at another workshop. The customer complained of jerky steering while driving. The previous mechanic replaced the power transistors but failed to remove the residue of active chemical flux. This substance is used during soldering to improve metal wetting and must be removed after the work is completed; left on the board, it gradually destroyed the conductive tracks. During bench testing, the oscilloscope detected noise in the control signals that occurred during heating. With light pressure on the board, the unit generated a critical internal error. During actual driving, this could have led to a sudden shutdown of the amplifier or an unintended deviation of the wheels. Further operation of the unit was prohibited and it was replaced with a verified functional unit, with configuration data transferred.

An even stricter approach is applied to passenger safety systems, which include airbags and seatbelt pretensioners. Component-level repairs of such units are not performed at all: only a complete replacement of the unit with a functional one, linked to the vehicle's identification code. Pyrotechnic circuits are constantly ready to activate, so any error during repair can cause either premature deployment of the airbags under normal conditions or their failure in the event of an accident.

The relationship between system type, failure modes, and safety risks is summarized in Table 2.

Table 2. Safety risk assessment and validation strategy for automotive control units

System	Safety Level (ISO 26262)	Typical Failure Mode	Potential Consequence	Detection Method	Recommended Action
Electric Power Steering (EPS)	C–D	Signal noise due to flux residue; unstable transistor operation	Sudden loss of steering assist; unintended wheel movement	Oscilloscope signal analysis; thermal stress; mechanical probing	Reject unit; replace with verified functional unit
Anti-lock Braking System (ABS)	C–D	Voltage drop during pump activation; unstable control signals	Loss of braking control; increased stopping distance	Load testing; voltage monitoring; sensor signal simulation	Repair only if stable under load; otherwise replace
Electronic Stability Control (ESC)	C–D	Data bus errors; signal dropouts under dynamic load	Loss of vehicle stability during manoeuvres	High-speed signal simulation; bus load testing	Reject if packet loss or overheating occurs
Airbag Control Unit (SRS)	D	Memory corruption; trigger circuit instability	Airbag non-deployment or unintended deployment	Diagnostic scan; integrity check	No repair allowed; full unit replacement only
Seatbelt Pretensioner System	D	Fault in pyrotechnic trigger circuit	Failure to restrain passenger in collision	System-level diagnostics	No repair allowed; full unit replacement only

Source: Compiled by the author.

The study documents a three-step validation procedure for these systems. Using a diagnostic scanner, the pump and hydraulic valves are forced to activate, and the voltage on the circuit board is monitored at startup: if it drops, the power circuit has not been properly restored. After that, angular accelerations are simulated, and sensor signals are checked: noise or dropouts indicate a poor connection under the microchip. The final test loads the data bus with signals corresponding to movement at a speed of 120 km/h: if the processor begins to lose packets or overheats, the unit is not ready for operation.

Practice confirms an important conclusion: a unit with a latent fault is more dangerous than a unit with a complete failure. A completely faulty unit is immediately detected by the vehicle's self-diagnostic system and alerts the driver to the problem, which the driver can resolve before driving off. A unit with a latent defect responds normally to all checks during steady driving but fails during emergency braking or sharp maneuvers, when maximum performance is required. The IEC 61508 standard [8] defines such malfunctions as dangerous latent failures and sets the highest detection requirements for them. When working with safety system units, opting not to repair due to an unpredictable outcome is a more reasonable decision than risking leaving a latent defect.

6. Conclusions

The study shows that the reliability of a refurbished automotive printed circuit board is determined by a combination of four interrelated parameters: the quality of solder joints in accordance with the requirements of Class 2 or Class 3 under IPC-A-610H, the stability of supply voltages, the correctness of signals on data buses, and the integrity of data stored in memory. None of these parameters is sufficient on its own, and only their combination allows us to conclude that the unit is ready for installation in a vehicle.

Standard testing with power connection and a diagnostic scanner detects only a portion of possible faults. Defects in the interlayer transitions of the board and damaged solder joints of microchips with ball contacts are detected only under a load close to real-world conditions. Therefore, including load, thermal, and mechanical tests in the protocol is not an overkill but a necessary condition for the reliability of the repaired unit. The rate of repeat failures drops to 5–10% provided that the vehicle is diagnosed before repairs begin and the root cause of the malfunction is addressed, repairs are systematically documented, protection against static discharge is ensured, and the testing protocol is continuously improved after each warranty return.

The anti-lock braking system, electronic stability control, and electric power steering require inspection with mandatory activation of the actuators and a load-bearing tire test. Passenger safety units are not subject to component-level repairs: only complete replacement is permitted. The key observation, confirmed by practice: a latent fault in a safety system module is more dangerous than a complete failure, because it does not manifest itself during normal driving but fails precisely during emergency braking or a sharp maneuver. The established quality control algorithm can be applied in independent repair shops, while the issue of predicting the service life of restored soldered joints remains open for further research.

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