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ORGANIZATION OF THE REPAIR PROCESS FOR AUTOMOTIVE ELECTRONIC CIRCUIT BOARDS IN A SMALL SPECIALIZED SERVICE CENTER

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Abstract. *The repair of automotive electronic control units at the component level is a relatively new niche, where specialists' experience is accumulating much faster than the scientific and methodological foundation is being established. This article examines how this process is organized in a small specialized service center: from initial diagnostics and data backup to soldering operations and bench testing under real-world conditions. Shah et al. (2024) expect the number of embedded control units to rise from 200 to 700 million by 2030. High refurbishment costs make component-level repair increasingly important. The theoretical framework draws on IPC-7711D/7721D and ANSI/ESD S20.20-2021, as well as peer-reviewed publications from 2022–2025. To verify the theoretical propositions, materials from a structured interview with Y. Breusov, a practicing specialist, were utilized, based on a sample of 210 repaired circuit boards from 2023–2024, distributed by type as follows: 60% engine control units, 20% body control units, 10% airbag control units, 10% transmission control units. The analysis showed that the reliability of the result is determined by three conditions: backing up the unit's identification data prior to any soldering operations, testing under actual power load, and ensuring protection against static discharge in accordance with ANSI/ESD S20.20-2021.*

Keywords: *automotive electronics, printed circuit board, electronic control unit, vehicle diagnostics, quality control, electronics repair.*

Introduction. A modern passenger car is equipped with dozens of built-in electronic control units, each of which serves a specific function: engine operation, braking system, airbags, climate control, and multimedia. In premium models, the number of such units exceeds 80, and they constantly exchange data with each other via internal data networks [2]. The failure of a single unit leads to a loss of functionality or a complete shutdown of the vehicle.

The automotive electronics market is showing steady growth. According to Custom Market Insights (2024), its volume exceeded $340 billion in 2024, with an average annual growth rate of approximately 5% [3]. Shah et al. (2024) predict an increase in the total number of embedded control units worldwide from 200 to 700 million units by 2030, which accordingly increases the size of the market for their repair and maintenance [1].

A faulty control unit is repaired in two ways: complete replacement with a new unit or replacement of a specific faulty part inside the unit - an approach known as component repair. Component repair is significantly cheaper for the car owner and preserves the original settings programmed into the unit's memory. At the same time, the organization of such repairs in a small specialized service center remains insufficiently systematized in the scientific literature.

The purpose of this article is to systematize the organizational principles and technological processes of repairing automotive electronic circuit boards in a small specialized service center. To achieve this goal, the following tasks have been set: to characterize the specifics of diagnosing automotive electronic modules; to describe the technological structure

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of the repair process; to determine the role of specialized equipment and requirements for personnel qualifications; to examine approaches to quality and risk management.

Literature review

Scientific publications on the research topic focus on four subject areas, each covering a distinct aspect of component repair.

The market and architecture of automotive electronics. Shah et al. (2024) examine the evolution of control units and the application of artificial intelligence methods to improve their reliability. The authors note that a modern control unit integrates a microprocessor, memory, analog converters, and power switches into a single housing; therefore, the increasing complexity of the architecture simultaneously expands functionality and increases the likelihood of individual component failures [1]. McKinsey (2024) notes in an industry review a shift from a distributed architecture, in which each function is handled by a separate unit, to a zonal architecture, where several powerful central processors control all of the vehicle's systems, which changes approaches to maintenance and repair [10].

On-Board Diagnostics and Communication Networks. Michailidis et al. (2025) review over 100 publications on the application of the second-generation on-board diagnostic system (OBD-II, On-Board Diagnostics II) for monitoring vehicle condition. The authors emphasize that OBD-II provides standardized access to fault codes and operating parameters of all systems in accordance with ISO 15031 and SAE J2012 [4]. Zhang et al. (2022) describe the operating principles of the Controller Area Network (CAN) and methods for detecting faults within it, including open circuits, short circuits, and conflicts between network nodes [5]. Anomalies in a vehicle's internal network are often the first measurable sign of a specific unit's malfunction even before visible damage appears.

Printed circuit board repair standards. The industry standard IPC-7711D/7721D regulates procedures for component replacement, repair of damaged conductive traces and contact pads, as well as work with integrated circuits in complex packages. The standard defines three levels of technician qualification, permissible heating temperature profiles, and material requirements [6]. PCBSync (2025) notes that replacing integrated circuits with ball grid array (BGA) packages corresponds to the highest level of complexity under this standard and requires precise instrumental temperature control [9].

Electrostatic Discharge (ESD) Protection. The ANSI/ESD S20.20-2021 standard establishes requirements for electrostatic discharge (ESD) control programs for organizations handling electronic components. The EOS/ESD Association (2021) notes that a static electricity discharge exceeding 100 volts can damage a microprocessor, and the damage may be latent: the unit functions normally for some time but fails later without any apparent external cause [7].

Despite the development of the scientific base in related fields, there is a lack of a systematic description of the organization of the full repair cycle for automotive electronic boards in small-scale service in the available literature, which explains the relevance of this study.

Materials and methods

This study employs a qualitative case-based design, combining a systematic literature review with empirical data from a single expert practitioner. The theoretical framework draws on IPC-7711D/7721D, ANSI/ESD S20.20-2021, and peer-reviewed publications from 2022 to 2025.

The empirical basis of the study was formed on the basis of a structured in-depth interview with Breusov, a practicing specialist in automotive electronics repair. The interview protocol included 30 open-ended questions regarding the repair process, equipment used, diagnostic methods, control unit data management, and handling of warranty claims. The specialist's sample includes 210 repaired electronic control units: 80 units in 2023 and 130

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units in 2024, reflecting a real annual increase in the volume of work of 62.5%. Distribution by unit type in the sample: engine control units account for 60% of the total, body control units account for 20%, airbag control units account for 10%, and transmission control units account for the remaining 10%. It should be noted that airbag control units in the sample did not undergo component-level PCB repair; for this category, Y. Breusov performs exclusively software adaptation and VIN binding using a replacement unit, which is consistent with the safety requirements described in Section 3.4. In the specialist's practice, vehicles from European manufacturers predominate due to their higher level of electronic integration. At the same time, as Y. Breusov notes, the classification of modules by complexity is determined by the module manufacturer itself, not by the vehicle brand: the same Bosch module can be installed on a Ford and a Volkswagen with minor differences in specifications.

Interview responses were systematically structured and grouped thematically to identify recurring patterns across repair cases. These data verify the theoretical propositions formulated on the basis of a literature review and are used as practical evidence to support them.

Specifics of diagnosing automotive electronic modules

Repairing an automotive control unit differs from repairing consumer electronics primarily due to the networked nature of automotive systems. Each control unit receives signals from sensors, processes them, and sends commands to actuators: fuel injectors, valves, and electric motors. At the same time, all control units constantly exchange data with one another, so a malfunction in one component may manifest as symptoms in a completely different part of the system.

Diagnosing automotive control units requires two levels of testing. The system level covers the vehicle as a whole and involves connecting to a standardized OBD-II diagnostic connector to read fault codes and current parameters of all systems. Michailidis et al. (2025) emphasize that OBD-II provides access to this data in accordance with ISO 15031 and SAE J2012, allowing for a systematic assessment of the vehicle's condition prior to removing any control unit [4]. Component-level diagnostics begins after the unit is removed and involves analyzing a specific circuit board using a microscope, an oscilloscope, and measuring instruments.

A system check is a mandatory prerequisite before removing the unit, and Breusov's practical data confirm its critical role. The specialist notes that in most cases, the root cause of the unit's failure lies not in the circuit board itself, but in the vehicle's external circuit. A representative example from the sample is a unit with a lack of power to the mass air flow sensor: after replacing the faulty power chip and installing the unit in the vehicle, the malfunction recurred because the power wire in the harness had a short to ground. Eliminating the short circuit along with re-replacing the chip resolved the issue. Zhang et al. (2022) describe typical CAN network faults, the detection of which requires oscillographic analysis of signal waveforms rather than merely measuring average voltage values, as noise anomalies remain invisible to a multimeter [5]. This fact is confirmed by Y. Breusov's observations: despite formally normal multimeter readings (2.6 V on the CAN-High bus and 2.4 V on CAN-Low), the oscilloscope detected noise pulses indicating a faulty network node.

Analysis of Y. Breusov's sample reveals a clear distribution of board damage types (Figure 1), summarized in Table 1 below. The prevalence of thermal damage (60%) indicates a systemic problem of unqualified interference with vehicle electrical circuits, which inflates repair demand relative to natural component wear.

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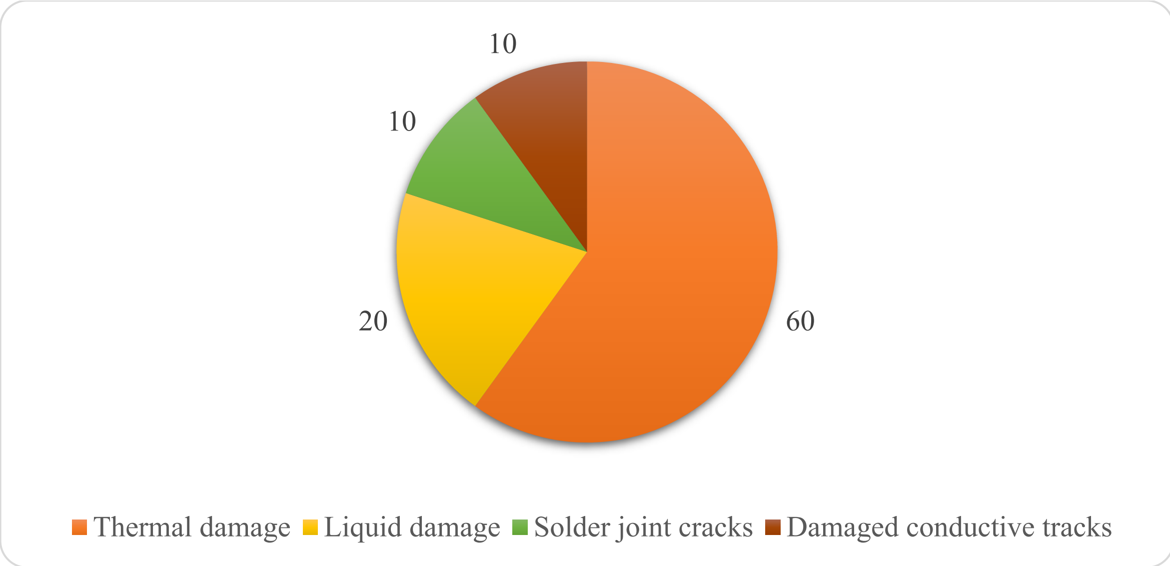

Figure 1. Distribution of Board Damage Types

Table 1. Distribution of Board Damage Types (n = 210)

Damage type	*Share, %*	*Primary cause*
Thermal damage	60	Unqualified interference with vehicle wiring
Water/liquid ingress	20	Operating in high-humidity conditions
Physical cracks	10	Mechanical stress or vibration
Damaged conductive tracks	10	Corrosion or mechanical impact

Component diagnostics are performed under a microscope, as the small size of modern components makes it impossible to detect damage with the naked eye. In his practice, Y. Breusov uses a professional optical microscope with a magnification range of 7x–45x. A 7x magnification is used during soldering operations, while a 45x magnification is used when searching for microcracks and defects in contact pads. A telling example from the sample is a unit with an unstable sensor power supply: only under side lighting at 45x magnification was it possible to detect a hairline crack in the ceramic capacitor. The crack behaved like a thermosensitive switch: when the board was heated, it expanded and the capacitor shorted the power supply to the case; when cooled, the short disappeared.

To detect faults that occur irregularly or only under certain conditions, Breusov uses four methods. Long-term recording with an oscilloscope in automatic save mode allows the cause of the failure to be recorded even in the absence of an operator. The thermal shock method involves rapidly cooling the board to minus 40 degrees Celsius, followed by heating to plus 90 degrees: damaged solder joints open up under such temperature fluctuations, and the defect is localized. Thermal imaging under load detects components heating up above normal levels even before final failure. Mechanically tapping the board with a plastic probe while the unit is running allows for the localization of unreliable contacts based on signal response.

A false initial conclusion is a known risk of component diagnostics. According to Y. Breusov, a false initial conclusion occurs in approximately one out of thirty cases. A typical example is the repair of the engine control unit in a 2012 Volkswagen Passat (Bosch ME17.2.6): a visible leak in the capacitor seemed to be the obvious cause of the lack of a spark at the third ignition coil, but after its replacement, the problem persisted. A re-inspection revealed a blown coil control switch, which required separate replacement.

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The main methods used to detect intermittent faults are summarized in Table 2.

Table 2. Methods for Detecting Intermittent Faults

Method	*Description*	*Detection capability*
Oscilloscope (auto-record mode)	Long-term signal recording	Captures intermittent faults
Thermal shock	Cooling to −40°C, heating to +90°C	Reveals defective solder joints
Thermal imaging	Monitoring under load	Identifies overheating components
Mechanical tapping	Light tapping during operation	Detects unstable contacts

Assessing the condition of circuit boards after liquid ingress is a complex task in its own right, which Y. Breusov considers one of the most labor-intensive in his practice. Powering on a water-damaged unit is unacceptable, as water under voltage causes electrolytic destruction of the track metallization. The assessment procedure includes microscopic inspection for the presence of oxides and discoloration of the vias between circuit board layers, ultrasonic cleaning, and electrical resistance measurements on the main power lines. If liquid has penetrated between the internal layers and caused delamination or chemical damage to the material, restoring electrical connections between the layers is technically impossible.

The repair process: from fault diagnosis to testing

Repairing an automotive electronic circuit board is a strictly sequential technological process in which each subsequent stage is based on the results of the previous one. Based on the requirements of the IPC-7711D/7721D standard and documented data by Y. Breusov, six main stages have been identified. According to the specialist, the full repair cycle typically takes three to eight hours, distributed as follows: about 20% of the time is spent on initial diagnostics and data backup, about 60% on the repair itself, and the remaining 20% on final testing and adaptation.

This distribution is shown in Figure 2.

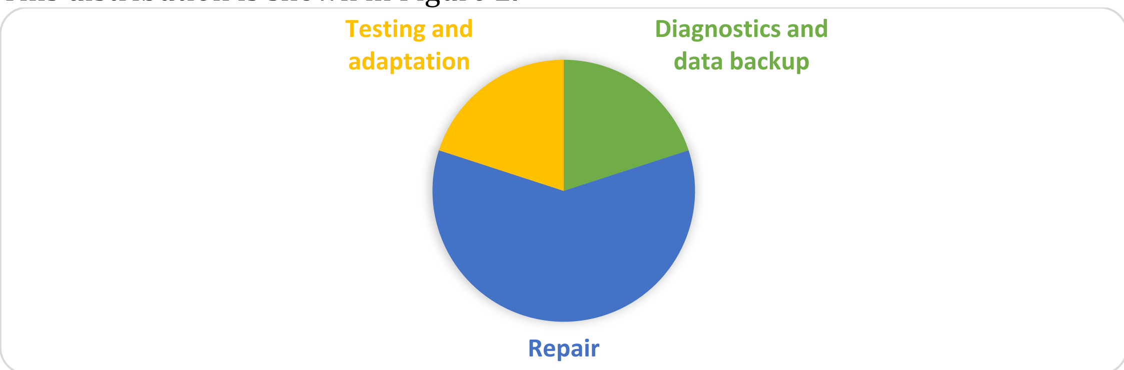

Figure 2. Time Distribution Across Repair Stages

Stage One: Initial Diagnostics and Data Backup (40–60 minutes). The unit is connected to a regulated power supply and measuring instruments. Current consumption in standby mode is the first diagnostic indicator: a deviation from the standard value in either direction indicates, respectively, a leak through a damaged component or an open circuit in the power supply. At the same time, a full backup of the unit's memory contents is performed using a programmer. The memory of each control unit stores the vehicle's unique identifier (VIN, Vehicle Identification Number), anti-theft system keys, configuration settings, and calibration data. Y. Breusov emphasizes that without completing this step, he does not touch a soldering iron and keeps at least two copies on different media. Loss of this data makes it impossible to pair the control unit with the vehicle, regardless of the quality of the physical repair performed.

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Stage Two: Opening, Cleaning, and Initial Defect Detection (up to 60 minutes). The unit's housing is opened, and the circuit board is examined under a microscope. If the board has been flooded with liquid, it is treated in an ultrasonic bath: ultrasonic waves generate millions of microscopic bubbles in the liquid, which, upon collapsing, remove salt deposits from beneath tightly soldered components. Y. Breusov uses a professional ultrasonic bath with distilled water and an alkaline concentrate at a temperature of 40–50 degrees Celsius for 5–10 minutes. Exceeding this time is undesirable, as prolonged vibration can disrupt the structure of soldered joints. After the bath, the board is rinsed with isopropyl alcohol and thoroughly dried.

Stage Three: The actual repair (two to four hours, about 60% of the total time). At this stage, faulty components are replaced, damaged conductive tracks are repaired using thin copper conductors, and microchips are re-soldered. Operations involving microchips in BGA-type packages, where the contacts are located beneath the package in the form of solder balls and are invisible from the outside, are the most technically complex. The IPC-7711D/7721D standard classifies their replacement as the highest level of complexity and specifies a precise heating temperature profile: a gradual rise to 217 degrees Celsius, a brief peak of 235–245 degrees Celsius, and controlled cooling [6]. Breusov uses a professional soldering station with UV curing capability and a bottom-heating table. According to the specialist, 90% of BGA chips seat correctly on the first attempt - this rate is achieved only through accumulated practical experience. The most common causes of failure during BGA assembly are excess flux, which causes the chip to shift during heating; residual moisture in the board, which turns into vapor when heated and destroys the layers; and unevenly cleaned contact pads, leading to the chip being mounted at an angle. PCBSync (2025) emphasizes that temperature is controlled by an external temperature sensor located directly next to the component, rather than by the soldering station's readings [9].

Step 4: Applying a protective coating. After repair, a thin conformal coating is applied to protect the board from moisture and salts. Temperature fluctuations under the hood can otherwise lead to rapid corrosion. Connectors, test pads, and heat-generating components are left uncoated to maintain contact and cooling.

Step Five: Bench Testing (20–30 minutes). The repaired unit is tested on a bench that simulates in-vehicle operating conditions. Y. Breusov monitors three critical parameters: current consumption (the normal value in standby mode for most units is 10–20 mA; a deviation indicates a short circuit or open circuit), voltages on the internal power lines (3.3 V, 5 V, 12 V), and the shape of the CAN bus signals (standard levels of 2.5 V, square waves without noise). A diagnostic scanner confirms the reading of the unit's identification data. Testing under actual load is mandatory: resistors or lamps that simulate the operation of injectors, ignition coils, or valves are connected to the unit's outputs. Stress tests include heating the board to 80–90 degrees Celsius to detect heat-sensitive microcracks and simulating voltage drops ranging from 9 volts during engine startup to 16 volts in the event of a faulty alternator.

Table 3. Main Stages of the Repair Process

Stage	Description
Stage 1	Diagnostics and data backup
Stage 2	Opening, cleaning, defect detection
Stage 3	Component repair and replacement
Stage 4	Protective coating
Stage 5	Bench testing
Stage 6	Installation and adaptation

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Stage Six: Installation and Adaptation in the Vehicle (approximately 60 minutes). The unit is installed in the vehicle, a unique identifier is programmed using a diagnostic scanner, the anti-theft system is synchronized, and the unit is adapted to the specific vehicle configuration.

The role of specialized equipment and staff qualifications

The technological complexity of repairing automotive electronic circuit boards directly determines the list of necessary equipment and the level of staff training. The absence of any of the key devices makes it impossible to perform certain types of operations and distinguishes a specialized service from a general auto repair shop. Breusov's workshop is equipped with a comprehensive set of equipment, including nine programmers of various types, two microscopes, a soldering station with UV heating, a heating table, three oscilloscopes, a laboratory power supply, a thermal imager, an ultrasonic bath, and signal generators. The core diagnostic and repair equipment is presented in Table 4.

A microscope is a basic tool for any operations involving a circuit board. The IPC-7711D/7721D standard establishes minimum magnification requirements depending on the type of operation [6]. According to Y. Breusov's observations, 7x magnification is sufficient for soldering operations, whereas 45x magnification is required for detecting microcracks and hairline shorts.

Table 4. Core Diagnostic and Repair Equipment

Equipment	*Function*	*Why it matters*
Optical microscope (7x–45x)	Detects micro-defects	Finds cracks and shorts invisible to the eye
Oscilloscope	Analyzes signal waveforms	Reveals anomalies not seen on a multimeter
Power supply (current limit)	Provides controlled power	Prevents damage in case of short circuits
Thermal imager	Shows heat distribution	Identifies overheating components early
Ultrasonic bath	Cleans boards after liquid damage	Removes contamination under components

An oscilloscope is an essential instrument for analyzing signals in automotive digital networks. Unlike a multimeter, which records only the average voltage value, an oscilloscope displays the signal waveform over time. Anomalies, such as rounded corners of square waves, indicate excessive capacitance in the circuit or problems with line matching. If the logic signal level is 3.2 V instead of the standard 5 V, this indicates a leak or degradation of the corresponding processor port. Additional repair and programming equipment is summarized in Table 5.

Table 5. Repair and Programming Equipment

Equipment	*Function*	*Why it matters*
Soldering station + bottom heating	Controlled soldering of multilayer boards	Prevents overheating and ensures proper soldering
Heating table	Preheats the board	Reduces thermal stress
Programmers (9 units)	Read/write ECU memory	Required for data access and restoration
Signal generators	Simulate input signals	Enable functional testing of the unit

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An adjustable power supply with current limiting capability replaces the car battery during bench testing. If there is an undiagnosed short circuit on the board, the power supply shuts down, preventing damage to the traces.

Thermal imager allows you to obtain the temperature distribution on the board surface under load. Damaged components heat up more than normal even before final failure, and short-circuit locations are immediately detected by localized spot heating.

Ultrasonic bath is used to clean boards after liquid has been poured onto them. The mechanism of action is based on cavitation: ultrasonic waves generate microscopic bubbles in the liquid, which, when collapsing, remove dirt and salts from surfaces inaccessible to mechanical cleaning.

A soldering station with bottom-side board heating is critically important when working with automotive circuit boards. Due to their multilayer construction and significant thermal mass, local heating with a heat gun from above without first evenly preheating the board from below leads to surface overheating and thermal damage to adjacent components before the solder in the lower layers reaches its melting point.

Programmers enable reading and writing the memory contents of control units. Breusov's workflow requires nine programmers of different types - for example, Magic Motorsport Flex - each supporting specific protocols and hardware interfaces. This arsenal is necessitated by the lack of a single unified solution: different car manufacturers and control unit manufacturers require different protocols and hardware interfaces to access memory.

The IPC-7711D/7721D standard classifies practitioners into three skill levels: basic, advanced, and expert [6]. Operations involving BGA chips and the restoration of internal circuit board layers fall under the expert level. Breusov’s documented experience confirms that achieving a consistent 90% success rate for first-time BGA installations requires extensive practical experience, not just theoretical training.

Skills in automotive electronics repair quickly become outdated without constant updates. Breusov spends at least an hour each day reviewing professional forums (MHH Auto, IATN), technical databases (Alldata, Direct Identifix), and manufacturer webinars (Autel, Xhorse). As automakers introduce new cryptographic protections for control units, tracking legitimate ways to work with these systems has become part of his daily routine.

Quality and risk management in the repair of automotive electronic circuit boards

Quality management in automotive electronics repair follows a different approach than in manufacturing. Each job is unique, and errors can lead to financial loss and safety risks.

Protection against static electricity. The static electricity charge on the human body can reach several thousand volts, which is sufficient to cause irreversible damage to a microprocessor upon unprotected contact. The ANSI/ESD S20.20-2021 standard defines three principles for controlling electrostatic discharge: grounding all conductive objects in the work area to a single potential; neutralizing charges on dielectric surfaces using ionizers; transporting sensitive components in antistatic packaging [7]. Breusov implements these requirements using an antistatic mat on the workbench, a grounding wrist strap, and grounding of the soldering tool. The hidden nature of ESD damage poses a particular danger: a unit may pass testing on the bench satisfactorily but fail after several weeks of operation without any visible external causes.

Spatial organization of the work area. Breusov identifies four functional zones: the diagnostic zone (clean equipment and measuring instruments, where unit connections and backups are performed), the disassembly and cleaning zone (where metal shavings and sealant residue accumulate), the soldering zone with an antistatic coating (microscope, bottom heating, heat gun), and the storage zone for finished units. The lack of separation between the dirty and soldering zones creates a risk of metal shavings falling onto the exposed circuit board during soldering operations, which can cause a short circuit between components.

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Management of control unit memory data. Each control unit stores an identification array: the vehicle identification number (VIN), anti-theft system keys, trim configuration, and calibration data. The management procedure includes pre-repair backup with duplication on two independent media, recalculation of checksums after any changes to the file (without this step, the module refuses to start or generates an "Internal Control Module Error"), as well as byte-by-byte verification of the saved file. A specific example from Y. Breusov's practice involves replacing a faulty BMW FRM lighting control unit with a used one from a donor vehicle: without transferring the VIN code and anti-theft system keys (ISN), the vehicle rejected the donor unit. Transferring the relevant data from the old module to the new one allowed for adaptation without involving an official dealer (Figure 3).

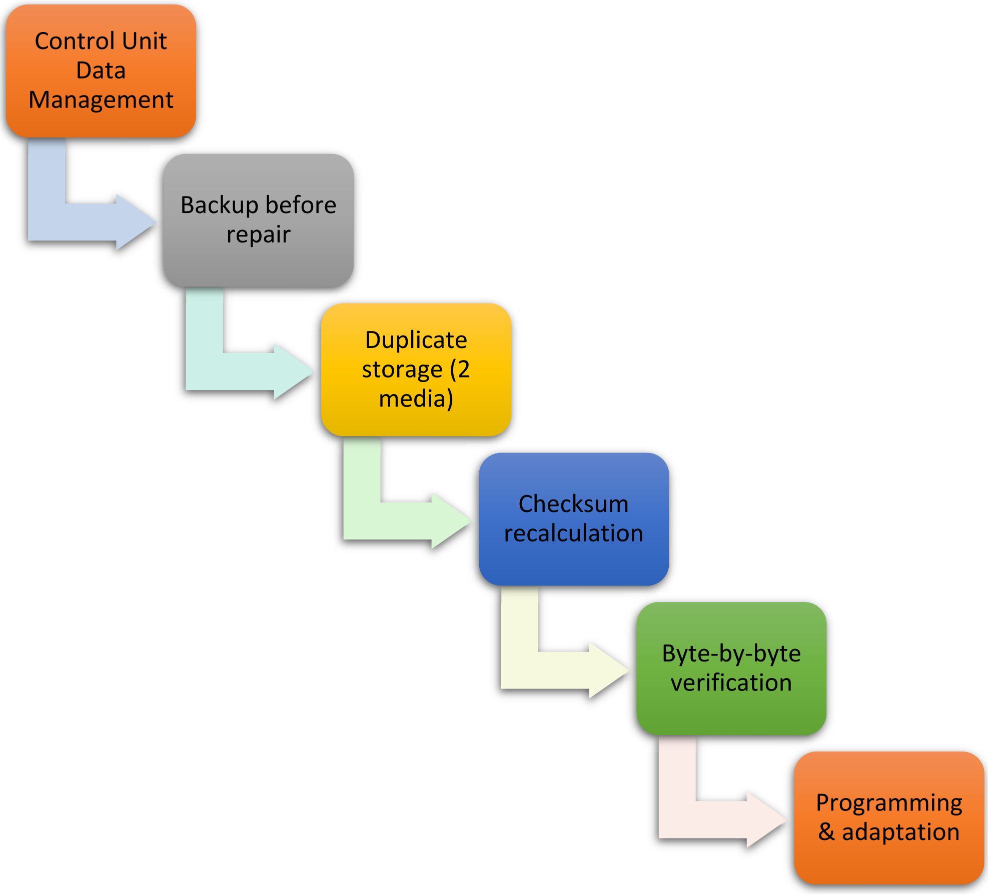

Figure 3. Data Management Workflow

Safety of repairs to active safety systems. The components of the anti-lock braking system (ABS), electronic stability control (ESC), and electric power steering (EPS) directly affect a vehicle's handling. The IPC-7711D/7721D standard establishes enhanced repair quality requirements for products in this class [6]. Y. Breusov provides a documented example: a Toyota power steering unit was received after a makeshift repair, with a complaint of spontaneous jerks of the steering wheel while driving. Residues of active solder flux between the pins of the control microcircuit caused current leakage when the unit was heated during driving, which could lead to unintended wheel turning or sudden disengagement of the power steering at speed. The only safe solution in such cases is to replace the unit.

Among the 210 repaired units, 10–12 cases (approximately 5–6%) were returned with repeat complaints. Root cause analysis identified three categories: vehicle-side faults not eliminated before repair (approx. 50% of complaints), component aging unrelated to the repair intervention (approx. 35%), and repair quality issues (less than 1% of the total sample).

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Together, these figures suggest that over 99% of repeat cases are attributable to systemic or aging factors rather than repair quality, underscoring the importance of thorough vehicle-level diagnostics prior to ECU removal. Based on the analysis of each warranty case, Breusov consistently updates the test protocol: specifically, following a repeat failure of the BMW FRM3 E70 headlight control unit, where the cause was the customer's use of non-standard LED bulbs with excessive inrush current, a load 20% higher than the nominal value was added to the testing standard. The review of complaints is based on a comparison of the unit's current condition with the data in the digital repair passport, which includes fault codes, software version, photographs of the circuit board at each stage, and memory dumps before and after intervention.

Prospects for the development of component repair. McKinsey (2024) notes the transition of automotive electronics to a zonal architecture with multiple central processors [10]. Shah et al. (2024) predict that the increasing complexity of multilayer boards and the cryptographic binding of components to a specific vehicle will limit the possibilities of physical component repair for the latest platforms (Figure 4) [1].

Figure 4. Shift in Repair Approach (5–10 years)

Breusov's practical observations align with these forecasts: in the latest models, even a perfectly replaced microchip will not function without authorization from the manufacturer's server. According to forecasts, over the next 5–10 years, specialized service centers will increase their investment in software tools and licenses for diagnostic software, while the role of purely hardware repairs will gradually diminish.

Discussion

This study contributes a structured description of the complete component-level repair cycle for automotive ECUs — a gap identified in the literature review, where existing publications address individual aspects (diagnostics, ESD protection, BGA rework) without integrating them into an organizational framework. The findings align with IPC-7711D/7721D requirements and extend them with practical performance indicators: a 90% first-pass BGA success rate and a 5–10% repeat failure rate with identifiable root causes.

Compared to manufacturing-focused studies, this work addresses the small-scale, single-specialist service context, where the absence of any key piece of equipment (e.g., oscilloscope, thermal imager, or programmer coverage) renders certain repair categories impossible rather than merely suboptimal.

The primary limitation of the study is its single-case design: findings are based on one specialist's documented practice and cannot be directly generalized to other service contexts. Future research should replicate this framework across multiple practitioners to test its validity and identify context-dependent variations.

Conclusions

The repair of automotive electronic circuit boards at the component level is a technologically complex activity that requires systematic process organization, specialized equipment, and formalized quality management. The study conducted allows us to formulate the following conclusions.

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Effective diagnostics requires a mandatory two-level check: a system-level check covering the vehicle as a whole, and a component-level check focused on a specific circuit board. Failure to perform a system-level inspection before removing the unit is the most common cause of recurring failures after repair: according to a sample study by Breusov, approximately 50% of complaints are specifically related to the fact that the root cause of the malfunction remained in the vehicle. The distribution of damage types in the sample (thermal - 60%, water - 20%, cracks - 10%, damaged tracks - 10%) indicates that human factors outweigh natural component wear.

The repair process follows six steps, starting with a backup of the unit's identification data before any soldering. In practice, time is split 20/60/20 between diagnostics, repair, and testing. Most of it goes into restoring components, with final testing under real-world load as a required step.

Repair quality is ensured by a system of complementary measures: protection against static electricity in accordance with ANSI/ESD S20.20-2021, bench testing under actual power load, and documentation of each repair with a record of the unit's condition before and after intervention. Achieving a consistent 90% success rate for first-pass BGA assembly, as documented in Breusov's practice, confirms compliance with the "Expert" level under IPC-7711D/7721D and serves as a marker of proficiency that cannot be attained through theoretical knowledge alone.

McKinsey (2024) and Shah et al. (2024) show that automotive control units are becoming more complex and more tightly protected. In newer models, a replaced microchip often won't work without manufacturer authorization. As a result, hardware repairs alone are no longer enough, and the focus is moving toward software tools and diagnostic access.

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