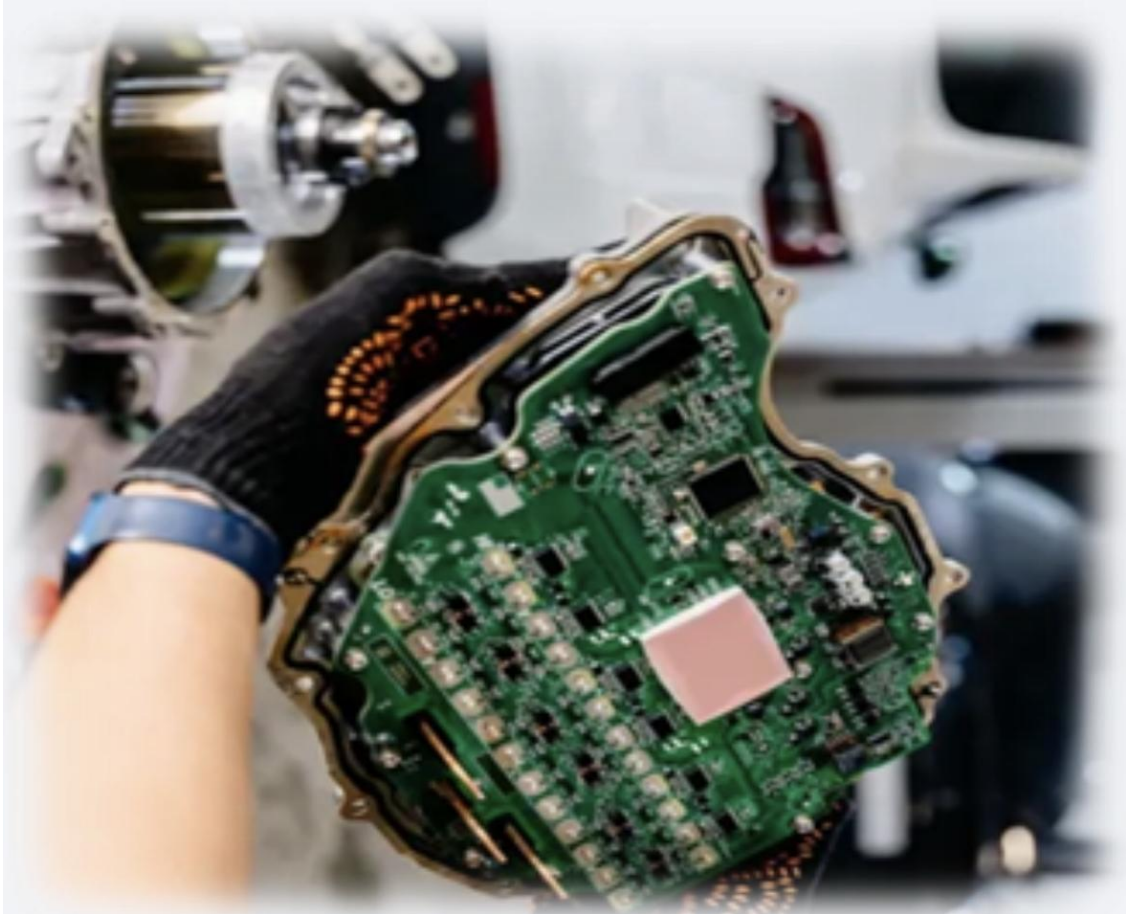




CHALMERS
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Data-Driven Requirement Development

From Field Data to Reliability Requirements: Identifying and Analyzing High-Performing Automotive ECUs

Master's thesis in Information and Communication Technology

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DEPARTMENT OF Electrical Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026
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Cover: An automotive electronic control unit assembly during inspection and validation analysis.

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Abstract

This thesis investigates a data-driven methodology for reliability-oriented requirement development in automotive electronics. Traditional automotive reliability engineering is primarily failure-focused, relying on warranty analysis and reactive investigation of defective components. However, such approaches provide limited understanding of why certain Electronic Control Units (ECUs) consistently demonstrate strong field reliability performance.

The research initially aimed to analyze relationships between ECU operational conditions and field reliability behavior through classical data-driven analysis. However, the required centralized operational-condition dataset was not available within the industrial data environment. Consequently, the study evolved toward a practical industrial screening methodology based on available enterprise engineering and field-quality data resources.

The proposed framework integrates multiple industrial datasets, including the KDP Engineering Database (KDP), Quality Follow-Up (QFU) warranty repair records, the Early Warning System (EWS), and procurement-related production volume data. By combining field repair occurrence with market exposure normalization, ECU populations with exceptionally low repair occurrence relative to deployment volume were identified.

Selected ECUs subsequently underwent hardware-oriented engineering investigation, including open-lid assessment, Printed Circuit Board (PCB)-level visual inspection, and review of available Design Verification (DV) and Product Validation (PV) documentation. The investigation focused on identifying recurring robustness-related engineering characteristics rather than performing direct failure analysis. Observed features included reinforced PCB mechanical support structures, controlled PCB cleanliness, environmental protection strategies, and evidence of robustness-oriented validation practices.

The work demonstrates how multiple industrial engineering and field-quality data sources can be systematically combined to support evidence-based reliability investigation and practical reliability requirement development in automotive electronics.

Keywords: Automotive Electronics, ECUs, Data-Driven Requirements Engineering, Field Reliability Assessment, Robustness Verification.

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YIMIN WANG, Gothenburg, June 2026

Declaration of AI Tool Usage

During this thesis work, artificial intelligence (AI) tools, primarily ChatGPT, were used as supportive tools for language improvement, text refinement, structure organization, and general programming assistance. AI-generated suggestions were also occasionally used to improve readability and clarity of written sections.

The AI tools were not used to generate research results, perform independent analysis, interpret experimental findings, or draw conclusions. All methodological decisions, data extraction procedures, analyses, interpretations, and conclusions presented in this thesis were developed and validated by the author.

The author assumes full responsibility for the content of this thesis and critically reviewed all AI-generated suggestions before incorporating them into the final manuscript. No confidential, proprietary, or sensitive information from Volvo Cars was intentionally disclosed to AI tools during the preparation of this work.

YIMIN WANG, Gothenburg, June 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

ADAS	Advanced Driver Assistance Systems
ASDM	Active Safety Domain Module
BOM	Bill of Materials
CMA	Compact Modular Architecture
CO	Change Order
DUT	Device Under Test
DV	Design Verification
ECM	Engine Control Module
ECU	Electronic Control Unit
ELP	Electrical Safety & Reliability team
EMC	Electromagnetic compatibility
EWS	Early Warning System
GDPR	General Data Protection Regulation
ISO	International Organization for Standardization
PCB	Printed Circuit Board
PII	Personal Identifiable Information
PV	Product Validation
QFU	Quality Follow-Up
SOD	Side Object Detection
VGM	Vehicle Gateway Module
VIN	Vehicle Identification Number

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1

Introduction

This chapter introduces the research background, motivation, problem formulation, research scope, and ethical considerations. It also explains the industrial context in which the study was conducted and defines the scope of the investigation.

1.1 Background

The automotive industry is currently navigating a radical paradigm shift towards Software-Defined Vehicles (SDVs). In this new era, vehicle functionality, performance, and the user experience are primarily governed by high-level software layers rather than being restricted to mechanical or hardware-bound features. Traditionally, automotive functions were “siloe”, where each mechanical assembly or hardware component performed a fixed, localized task. However, the modern industry is transitioning to highly integrated, centralized Electrical/Electronic (E/E) architectures. These architectures rely on a complex, interconnected network of Electronic Control Units (ECUs) that execute sophisticated logic, ranging from high-stakes autonomous driving algorithms to low-latency real-time infotainment systems.

While the industry’s strategic spotlight has moved toward software agility, the underlying hardware remains the critical physical foundation. As vehicle systems become more interdependent, the hardware complexity increases exponentially. This interdependence means that the robustness of a single high-performance ECU is no longer just a component-level requirement but a prerequisite for personal safety and reliability, operational availability, and long-term performance. Any hardware-level instability can cascade through the centralized architecture, potentially compromising numerous software-driven functions simultaneously.

Within this evolving and high-pressure landscape, Volvo Cars’ Electrical Safety & Reliability team (ELP) is tasked with the foundational mission of defining and developing rigorous requirements for electrical systems and components. Their objective is to maximize customer value across the vehicle’s full lifecycle, with a strategic focus on Reliability, Electrical Safety, and the Cost-of-Ownership of the electrical system.

Historically, hardware requirements were often developed based on localized engineering experience or reactive “failure-focused” engineering. However, as E/E complexity surpasses the limits of traditional intuition, it becomes difficult to maintain full visibility into how components actually behave under diverse global field conditions.

To overcome these challenges, there is an urgent need to transition from intuition-

based engineering towards a data-driven requirement development approach. By utilizing large-scale industrial field data, engineering teams can identify “gold standard” high-performing ECUs. This systematic approach allows for the extraction of empirical success patterns, which are then transformed into actionable, high-fidelity requirements for future vehicle generations, ensuring that hardware robustness keeps pace with software innovation.

1.2 Problem Discussion

1.2.1 The “Failure-Focused” Limitation

Traditional reliability engineering in the automotive sector has historically been “failure-focused,” relying heavily on reactive analysis. This approach primarily utilizes tools such as Warranty Claim Analysis and Design Failure Mode and Effects Analysis to identify and mitigate known defects.

While effective for resolving existing quality issues, this reactive stance is increasingly insufficient for the rapid development cycles of modern E/E architectures. A significant limitation of this conventional methodology is its “blind spot” towards success components: while vast resources are spent investigating why components fail, very little systematic effort is dedicated to understanding why certain components consistently perform exceptionally well under field conditions.

Consequently, valuable engineering insights embedded within “high-performing” units—those with zero or near-zero failure rates despite high market exposure—remain largely untapped. This lack of visibility into the characteristics of success prevents engineers from proactively integrating proven robust design patterns into new requirement specifications.

1.2.2 The Proposed Solution: Data-Driven Method

To bridge this gap, this research proposes a proactive, data-driven methodology that shifts the analytical focus from failure logs to success patterns. Unlike traditional hardware engineering tasks, this project involves a significant exploratory component, requiring a deep contextual understanding of Volvo’s internal data architecture. The core objective is to develop a structured analytical framework that utilizes raw industrial data to inform actionable hardware requirements—an area where the data’s full potential has yet to be extensively explored within the hardware-focused team.

This project is carried out through an iterative discovery process, structured into two distinct phases:

- Phase 1: Knowledge Discovery and Data Integration. This phase represents the primary focus of the research, emphasizing the exploration and synthesis of disparate databases. It involves identifying the right data sources, understanding their underlying logic, and resolving data gaps—such as the mapping between Part Numbers and Exchange Numbers, to isolate the true “gold standard” ECUs from thousands of candidates.

- Phase 2: Technical Investigation and Requirement Formalization. This phase transitions from data-driven identification to engineering-driven verification. The identified high-performing units undergo a comprehensive “deep-dive” analysis, which involves reviewing historical design artifacts. Furthermore, physical investigations, including lid-open analysis and hardware teardowns, are conducted to uncover the underlying design choices responsible for their superior reliability. Finally, these empirical insights are synthesized and formalized in a set of standardized requirements or checklists to guide future hardware development.

1.3 Field Data and Industrial Data Context

In the automotive industry, field data refers to empirical information collected from vehicles after customer delivery and during operation in real-world environments. Unlike laboratory test data or simulation results, field data reflects the actual performance of components under diverse driving behaviours, climatic conditions, road environments, and usage patterns.

In this thesis, field data is primarily represented by warranty claims and service repair records. These records provide practical evidence of how electronic components behave in customer vehicles and therefore form an important basis for reliability-oriented analysis. However, field repair data alone is not sufficient for identifying genuinely reliable components. A component with few recorded repairs may either be robust or simply have limited market exposure.

For this reason, the field repair records were interpreted together with internal engineering and production-related data. Engineering product-structure information was used to identify relevant ECU part numbers and their relationships, while production-volume information was used to approximate market exposure. This combination allowed repair occurrence to be evaluated in relation to the population at risk, rather than as an isolated repair count.

The detailed industrial data infrastructure, including the specific Volvo Cars systems, data extraction procedures, and cross-referencing logic, is described in Chapter 3.

1.4 Scope and Research Subject: ECUs within the CMA Platform

To ensure the validity and consistency of the data-driven analysis, this research is bounded within a specific technical environment: the Compact Modular Architecture (CMA) platform and its associated ECUs. Defining this scope is essential, as the reliability of an electronic component is inherently linked to the vehicle architecture and system environment in which it operates.

1.4.1 Introduction of Vehicle Platforms: CMA and SPA

In the automotive engineering context of Volvo Cars, a platform is defined as a modular vehicle architecture that determines the physical structure, powertrain layout, and, most importantly, the baseline E/E architecture.

- Compact Modular Architecture (CMA) is a modular vehicle platform developed by Volvo Cars for compact and mid-sized vehicles. CMA defines a common structural and E/E architecture that enables extensive reuse of components, systems, and ECUs across multiple vehicle models and production years. From an E/E perspective, the CMA platform supports a relatively centralized and standardized architecture, providing a controlled level of complexity while enabling advanced functionalities such as driver assistance systems, connectivity, and infotainment. This architectural consistency makes CMA particularly suitable for large-scale field data analysis, as ECU configurations and system interactions remain largely comparable across the vehicle population.
- The Scalable Product Architecture (SPA) is Volvo Cars' modular platform designed for larger and more premium vehicle segments. SPA supports a broader range of vehicle sizes, powertrain solutions, and advanced feature sets, resulting in a more complex and heterogeneous E/E architecture compared to CMA.

1.4.2 ECUs as Physical Implementation Entities

Within the platform, ECUs serve as the distributed intelligence nodes responsible for executing the platform's systemic logic. For the purpose of this research, an ECU is strictly defined as an embedded system characterized by its integration of microprocessors and associated circuitry onto a Printed Circuit Board (PCB). These units represent the physical realization of the E/E architecture defined at the platform level.

The technical density of an ECU is derived from its complex internal composition. By establishing the presence of a PCB as a primary scoping criterion, this study excludes simpler electromechanical components, focusing instead on the most technically complex and reliability-critical elements of the vehicle. These units must maintain precise electrical performance while being subjected to the harsh environmental constraints dictated by the physical layout.

1.5 Sustainability and Ethics

In alignment with modern engineering standards and Volvo Cars' corporate values, this research integrates considerations of sustainability and professional ethics into the process.

1.5.1 Environmental Sustainability

The primary contribution of this study to environmental sustainability lies in the enhancement of hardware longevity and resource efficiency. By identifying the design

characteristics of high-performing ECUs, the research aims to establish more robust hardware requirements that ensure the operational lifespan of vehicle components.

- **Waste Reduction:** Improved reliability directly translates to a reduction in premature hardware failures, thereby minimizing the generation of electronic waste (E-waste) throughout the vehicle's lifecycle.
- **Logistical Footprint:** Minimizing field repairs reduces the carbon emissions associated with global spare parts logistics, dealership service operations, and the manufacturing of replacement units.

1.5.2 Data Ethics and Privacy

The handling of industrial data within this study follows strict ethical and security protocols to protect both customer privacy and corporate interest.

- **Anonymization:** All vehicle-level data, including Vehicle Identification Numbers (VINs), are anonymized. These identifiers are used solely as internal keys for cross-referencing databases and are never disclosed in the final thesis.
- **General Data Protection Regulation (GDPR) Compliance:** No Personal Identifiable Information (PII) is utilized or processed. The analysis focuses exclusively on the technical performance of hardware components and repair history.
- **Proprietary Protection:** Sensitive commercial and technical details — such as supplier names, specific part costs, and patented designs — are abstracted or generalized to safeguard Volvo Cars' competitive advantage.
- **Secure Environment:** No raw or sensitive data is stored on unauthorized personal devices or public platforms.

2

Theory

This chapter presents the theoretical background supporting this thesis. It introduces reliability engineering concepts, the role of field data in reliability assessment, common PCB reliability challenges, and robustness verification methodologies relevant to automotive electronics.

2.1 Reliability Engineering in Automotive Electronics

Reliability engineering plays an important role in the development of automotive electronic systems, since electronic components are required to operate under highly variable environmental, mechanical, and electrical conditions throughout long vehicle lifetimes. In general terms, reliability refers to the ability of a product or system to perform its intended function without unacceptable failure under specified operating conditions and over a specified period of time. For automotive electronics, this is particularly relevant because ECUs are continuously exposed to temperature variation, vibration, humidity, electrical disturbances, contamination, and ageing effects during vehicle operation. The ISO 16750 standard provides a standardized framework describing environmental conditions and testing methods for electrical and electronic equipment used in road vehicles, including mechanical, climatic, and electrical stresses associated with automotive operating environments[1].

In modern vehicles, ECUs are central elements of the electrical and electronic architecture. They implement and coordinate functions through embedded hardware, software, sensors, actuators, communication interfaces, and power electronics. As vehicle systems become increasingly interconnected and software-dependent, the reliability of individual ECUs becomes increasingly important at system level. Failures in a single ECU may influence not only the local functionality of the affected unit, but also the stability and availability of dependent vehicle systems.

To address these challenges, reliability-oriented engineering practices are widely integrated into automotive product development. Such practices typically include design-for-reliability principles, environmental qualification, validation testing, manufacturing quality control, and robustness-oriented verification activities. Bosch describes reliability as a key product characteristic that must be considered throughout product development, verification, and validation processes[2]. Similarly, the ZVEI Handbook for Robustness Validation of Automotive Electrical/Electronic Modules describes robustness validation as a methodology intended to ensure that automotive electronic products can tolerate environmental, manufacturing, and operational

variation without unacceptable degradation during their intended service life[3]. Traditional reliability investigations often focus primarily on failed products and field-returned components in order to identify design weaknesses or failure mechanisms. However, products demonstrating strong field reliability may also provide valuable engineering insights. ECU platforms with low repair occurrence despite high production exposure may reflect beneficial design practices, manufacturing quality characteristics, environmental protection strategies, or validation approaches associated with robust product development.

This thesis adopts this broader reliability engineering perspective. Instead of focusing exclusively on failed ECUs, the study investigates ECU populations demonstrating strong field performance and explores whether recurring hardware-related or validation-related characteristics can be identified among these selected units. In this context, reliability engineering provides the theoretical basis for combining field repair information, production exposure data, PCB-level observations, and available validation documentation as part of a broader engineering investigation into high-reliability automotive ECU platforms.

2.2 Field Data in Data-Driven Reliability Engineering

2.2.1 Operational Data and Industrial Data Availability

The increasing digitalization of modern vehicles has led to growing interest in data-driven methodologies within reliability engineering and product development. Large-scale operational datasets collected from connected vehicles, onboard diagnostics, embedded sensing systems, and industrial monitoring platforms have created new possibilities for reliability-oriented analysis and engineering decision support. Data-driven approaches may support predictive maintenance, degradation analysis, fault detection, reliability prediction, and requirement development through the analysis of operational and field-related data[4][5].

In theory, advanced data-driven reliability investigations can utilize operational variables such as temperature exposure, electrical loading, vibration levels, environmental conditions, driving behavior, accumulated operating time, and other ECU-related usage signals. Under sufficiently structured and traceable data conditions, statistical analysis, machine learning methods, clustering techniques, correlation analysis, and pattern recognition approaches may be used to identify relationships between operational conditions and field reliability performance[5][7].

At the same time, the increasing complexity of automotive electronics has created new reliability challenges associated with highly integrated systems, diverse operating conditions, and long product lifetimes. Rzepka et al. emphasize that next-generation automotive electronics require application-driven reliability approaches capable of handling complex interactions between operational environments, usage conditions, and electronic system behavior[6]. This further strengthens the relevance of operational and field-oriented data in modern automotive reliability engineering. The initial conceptual direction of this thesis was aligned with this type of op-

erational data-driven investigation. The original expectation was that centralized datasets containing ECU-related operational and environmental variables would be available across multiple ECU populations. Under such conditions, it would theoretically be possible to investigate how operational usage patterns and environmental exposure correlate with reliability performance and field behavior.

However, practical industrial environments often present substantial limitations regarding operational data availability, accessibility, consistency, and traceability. In many cases, operational signals are distributed across multiple systems, unavailable historically, difficult to associate directly with specific ECU hardware variants, or inaccessible due to organizational and technical constraints. As the project progressed and the industrial data infrastructure was investigated in greater detail, it became evident that the type of centralized operational dataset initially envisioned was not realistically available within the scope of this study.

Consequently, the investigation methodology was adapted toward a more practically accessible field-oriented reliability approach. Instead of relying primarily on large-scale operational signal analytics, the study focuses on the structured use of available engineering databases, repair records, production exposure data, and engineering traceability systems in order to identify ECU populations demonstrating strong field reliability performance.

In this context, the term data-driven in this thesis does not primarily refer to the application of advanced machine learning models, but rather to the systematic use of available industrial data sources to support evidence-based reliability investigation and comparative ECU selection.

2.2.2 Warranty and Repair Data in Reliability Investigation

Field reliability assessment is an important concept within reliability engineering because it evaluates product behavior under actual operational conditions rather than controlled laboratory environments. In automotive electronics, field reliability observations are obtained from deployed vehicle populations operating under varying environmental conditions, usage profiles, driving behavior, and service lifetimes. Consequently, field-related information provides an important basis for understanding how electronic systems behave during real-world operation[8].

A central challenge in field reliability assessment is the interpretation of failure occurrence across different product populations. Absolute failure or repair counts alone are generally insufficient for meaningful comparison, since larger production populations naturally tend to generate more diverse types of recorded failures. Reliability-oriented field analysis therefore commonly considers operational exposure or population exposure when evaluating field performance. In practice, this often involves relating observed failure occurrence to production volume, installed population, or accumulated operational exposure in order to achieve more representative comparison between different product populations[9].

Another important aspect of field reliability assessment is uncertainty associated with field data interpretation. Field-related records may contain incomplete information, inconsistent failure descriptions, duplicated events, or service actions that do not necessarily correspond to confirmed hardware failures. In addition, field

observations are influenced by varying operational environments and customer usage conditions, which may complicate direct interpretation of reliability behavior. Consequently, field reliability analysis often requires filtering, categorization, and cautious interpretation of observed field events.

Despite these limitations, field-related information remains an important complement to laboratory validation activities. Laboratory testing evaluates products under predefined and controlled stress conditions, whereas field observations reflect accumulated operational exposure across large product populations and long service durations. As a result, field reliability assessment continues to play an important role within automotive reliability engineering and reliability-oriented product evaluation[8].

2.3 Reliability Challenges in Automotive PCB Assemblies

2.3.1 Environmental and Mechanical Stress Factors

Automotive electronic control units operate under significantly harsher environmental and mechanical conditions than conventional consumer electronic systems. During vehicle operation, ECUs may be exposed to continuous temperature variation, thermal cycling, mechanical vibration, humidity, contamination, electrical disturbances, and long-term ageing effects. The severity and interaction of these stress conditions depend on factors such as vehicle architecture, installation location, operating environment, and service conditions. The International Organization for Standardization (ISO) 16750 series defines standardized environmental conditions and corresponding test procedures for electrical and electronic equipment used in road vehicles, including thermal, mechanical, climatic, and electrical stress categories[1].

In reliability engineering, environmental and mechanical stress factors are important because they may initiate progressive degradation mechanisms within PCB assemblies and electronic interconnections. Reliability degradation in automotive electronics is therefore commonly understood as a time-dependent process in which repeated stress exposure gradually affects materials, interconnections, insulation properties, and mechanical stability. Table 2.1 summarizes several common environmental and mechanical stress factors together with representative degradation mechanisms and potential reliability impacts.

Table 2.1: Typical Environmental and Mechanical Stress Factors in Automotive PCB Assemblies

Stress Factor	Typical Degradation Mechanism	Potential Reliability Impact
Thermal cycling	CTE mismatch fatigue	Solder crack initiation
Mechanical vibration	Mechanical fatigue accumulation	Connector degradation
Humidity and moisture	Corrosion and electrochemical migration	Leakage current
Contamination	Insulation degradation	Electrical instability
Mechanical loading	PCB stress accumulation	Structural degradation

Among these stress factors, thermal cycling represents one of the most important reliability challenges for PCB assemblies and solder interconnections. Temperature variation causes repeated mechanical expansion and contraction of materials with different coefficients of thermal expansion (CTE). Over time, accumulated thermo-mechanical strain may contribute to solder fatigue, crack initiation, interconnect degradation, and material delamination within electronic assemblies[6][10].

Mechanical vibration and shock additionally represent major reliability concerns in automotive electronics. Vehicle operation continuously exposes ECUs to vibration originating from road conditions, drivetrain systems, engine operation, and structural excitation. Repeated vibration exposure may gradually accumulate mechanical stress within solder joints, connectors, PCB mounting regions, and mechanically unsupported structures. Such degradation mechanisms may contribute to connector instability, solder cracking, and long-term fatigue-related reliability degradation[6].

Environmental exposure also plays an important role in automotive ECU reliability. Humidity, moisture ingress, salt contamination, dust, and chemical exposure may interact with electrically sensitive PCB regions and contribute to corrosion, leakage currents, insulation degradation, and electrochemical migration phenomena. These degradation mechanisms may become increasingly severe when combined with thermal cycling, contamination accumulation, and extended operational exposure[3].

In practice, automotive electronic assemblies are rarely exposed to only one individual stress factor. Instead, degradation mechanisms often develop under combined environmental, thermal, and mechanical stress interaction during long-term vehicle operation. Consequently, automotive PCB reliability represents a multidisciplinary engineering challenge involving material behavior, mechanical robustness, environmental protection, manufacturing quality, and long-term degradation prevention strategies. For this reason, automotive ECU development commonly includes environmental qualification, vibration testing, thermal validation, and robustness-oriented design practices intended to reduce susceptibility to long-term degradation mechanisms.

2.3.2 PCB-Level Reliability Protection and Robustness

Automotive PCB assemblies are required not only to provide electrical functionality, but also to maintain stable operation under long-term thermal, mechanical, and environmental stress exposure. As discussed in the previous section, automotive ECUs are continuously subjected to multiple interacting degradation mechanisms during vehicle operation. Consequently, modern automotive electronics development commonly applies robustness-oriented design principles intended to reduce the probability, severity, and progression rate of long-term degradation phenomena within electronic assemblies.

From a reliability engineering perspective, PCB-level protection strategies are generally not intended to eliminate environmental exposure completely. Instead, such strategies aim to limit the interaction between external stress conditions and electrically or mechanically sensitive regions of the PCB assembly. In practice, automotive electronic assemblies are therefore commonly designed with consideration for environmental protection, mechanical stability, manufacturing quality, and resistance to degradation mechanisms associated with long-term field operation.

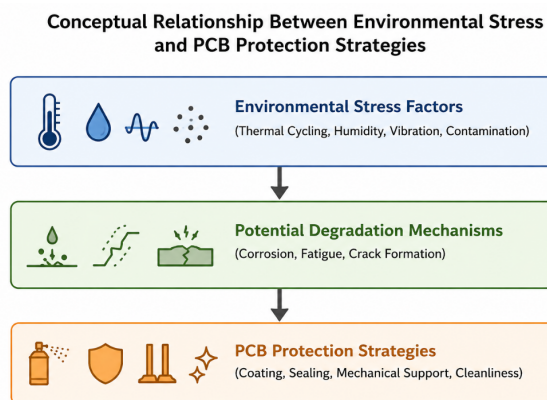


Figure 2.1: Conceptual Relationship Between Environmental Stress and PCB Protection Strategies

One important aspect of PCB robustness is protection against moisture, contamination, and corrosive exposure. Environmental factors such as humidity, condensation, salt contamination, and chemical exposure may interact with electrically sensitive PCB regions and contribute to corrosion, leakage currents, insulation degradation, and electrochemical migration phenomena over time. Protective strategies such as conformal coating, housing sealing, protective enclosure structures, controlled PCB cleanliness, appropriate manufacturing processes, design-for-manufacturing practices, suitable soldering materials, and robust component selection are commonly used to reduce environmental interaction and improve long-term PCB robustness[3]. Conformal coating is widely applied in automotive electronics as a protective polymer layer intended to improve resistance against moisture-related and contamination-related degradation mechanisms during long-term vehicle operation.

Mechanical robustness is another important consideration in automotive PCB reliability. Press-fit connector technology is widely adopted in automotive electronics

to provide reliable solder-free electrical interconnections between connectors and PCBs. Compared with conventional soldered connector pins, press-fit interconnections reduce solder-joint fatigue under vibration and thermal cycling while maintaining stable electrical contact over long-term operation. During vehicle operation, PCB assemblies are continuously exposed to vibration, shock, connector loading, and thermal expansion effects. Repeated stress accumulation under such conditions may contribute to fatigue-related degradation mechanisms within solder interconnections, mechanically loaded regions, and connector structures. Consequently, PCB mounting structure, component placement, stress distribution, connector support, and solder joint integrity may significantly influence long-term durability and resistance to mechanical fatigue phenomena[6][10]. Mechanical support strategies are therefore commonly implemented in order to reduce localized stress concentration and limit the progression of mechanically induced degradation mechanisms.

Manufacturing quality additionally plays a significant role in PCB reliability performance. Defects introduced during manufacturing may act as initiation points for long-term degradation mechanisms under combined environmental and mechanical stress exposure. Factors such as solder joint quality, PCB cleanliness, surface finish quality, and process consistency may therefore influence the long-term stability of electronic assemblies. One common manufacturing-related imperfection is solder void formation, where air or flux residues become trapped within solder joints during the soldering process. Excessive solder voids may reduce the effective load-bearing area of solder joints, increasing their susceptibility to thermomechanical fatigue and long-term reliability degradation under vibration and thermal cycling. Residual contamination originating from manufacturing processes, including flux residue or insufficient cleaning, may increase susceptibility to corrosion-related degradation under humid operating conditions.

Tin whiskers are spontaneous metallic filaments that may grow from tin-plated surfaces under long-term mechanical stress or environmental exposure. In automotive electronics, whisker growth can create unintended electrical bridges between adjacent conductors, potentially resulting in intermittent or permanent short circuits. Consequently, the absence of whisker formation is commonly used as an indicator of good long-term PCB reliability.

Because multiple degradation mechanisms may interact simultaneously during long-term vehicle operation, automotive PCB robustness is typically achieved through the combined effectiveness of several protection and reliability-oriented design strategies rather than through one isolated design feature. Environmental protection strategies, mechanical design practices, manufacturing quality control, material selection, and validation-oriented engineering activities therefore collectively contribute to long-term field reliability performance. Consequently, PCB-level reliability protection represents an important aspect of automotive ECU robustness engineering and degradation mitigation throughout the intended operational lifetime.

Table 2.2: Protection Strategies and Reliability Objectives for PCB Assemblies

Protection Strategy	Reliability Objective
Conformal coating	Reduce moisture and contamination interaction
Controlled PCB cleanliness	Reduce corrosion-related degradation risk
Robust solder interconnections	Improve resistance to vibration fatigue
Mechanical support structure	Reduce localized stress accumulation
Housing sealing	Limit moisture ingress and environmental exposure

2.4 Design Verification and Product Validation in Automotive Electronics

2.4.1 Validation Philosophy and Robustness Verification

Robustness verification in automotive electronics is based on the principle that long-term degradation mechanisms can be evaluated through controlled stress exposure during product development. Because many reliability-related degradation processes develop progressively over time, validation methodologies commonly attempt to reproduce representative environmental, thermal, mechanical, and electrical stress conditions capable of accelerating or exposing potential weaknesses within electronic assemblies[3][11].

From a reliability engineering perspective, validation activities are therefore not limited to confirming immediate functional correctness. Instead, robustness verification focuses on evaluating the ability of electronic systems to tolerate expected operational stress exposure without unacceptable degradation of electrical, mechanical, or functional performance. Validation frameworks in automotive electronics are consequently closely associated with degradation-oriented engineering concepts such as fatigue accumulation, corrosion susceptibility, thermomechanical strain, insulation degradation, and long-term material stability.

Automotive validation methodologies commonly distinguish between Design Verification (DV) and Product Validation (PV). DV primarily focuses on robustness characterization of the product design itself under defined qualification conditions. In this context, controlled stress exposure is used to evaluate whether the design architecture, material selection, interconnection structure, and protection strategies demonstrate sufficient robustness against representative degradation mechanisms. PV, in contrast, focuses more strongly on evaluating robustness consistency under production-representative conditions, including manufacturing-related variation and process-related influence factors[3].

A central principle within robustness-oriented validation philosophy is that degradation mechanisms should ideally be identified before large-scale field exposure occurs. Validation activities therefore commonly utilize accelerated or representative stress conditions intended to reveal susceptibility to long-term degradation phenomena during qualification stages rather than during vehicle operation. Such approaches are widely associated with physics-of-failure-oriented reliability engineering methodologies, in which stress exposure is used to evaluate degradation progression and

robustness limitations within electronic assemblies[11].

At the same time, robustness verification cannot fully reproduce all possible field operating conditions or long-term usage scenarios. Consequently, validation activities are generally understood as engineering approximation frameworks intended to improve confidence in product robustness rather than to guarantee complete elimination of future field failures. Nevertheless, the breadth, maturity, and consistency of validation activities are commonly regarded as important indicators of robustness-oriented engineering development within automotive electronics projects[3][12].

Validation philosophy in automotive electronics therefore represents a reliability-oriented engineering framework in which controlled stress exposure, degradation-oriented qualification, and robustness assessment are collectively used to support long-term operational reliability under expected vehicle conditions.

2.4.2 Common Validation Categories in Automotive Electronics

Validation categories in automotive electronics are generally structured around the principle that different stress conditions may activate different degradation mechanisms within electronic assemblies. Consequently, automotive robustness qualification frameworks commonly utilize multiple validation methodologies intended to expose susceptibility to thermal, mechanical, electrical, and electromagnetic stress-related degradation phenomena under controlled qualification conditions[1][3].

Environmental qualification testing is primarily associated with degradation mechanisms related to thermal exposure, humidity, condensation, corrosion, and long-term environmental ageing.

Environmental stress conditions may contribute to thermomechanical fatigue accumulation, material degradation, insulation instability, corrosion-related phenomena, and moisture-induced degradation mechanisms within PCB assemblies and electronic interconnections. Validation methodologies such as thermal cycling, humidity exposure, and combined environmental stress testing are therefore commonly used to evaluate the robustness of electronic assemblies against progressive environmentally induced degradation processes[1][6].

Mechanical validation activities are similarly based on the principle that cyclic mechanical loading may progressively degrade solder interconnections, connector structures, mounting regions, and mechanically stressed PCB areas. During vehicle operation, automotive ECUs are continuously exposed to vibration and shock originating from road excitation, drivetrain systems, engine operation, and structural resonance phenomena. Mechanical qualification methodologies are therefore commonly intended to expose fatigue-related degradation mechanisms associated with repeated stress accumulation and long-term mechanical loading conditions[6][10].

Electrical robustness validation focuses primarily on degradation susceptibility associated with electrical overstress conditions. Automotive electronic systems may experience voltage variation, transient disturbances, polarity-related stress, and power-related abnormalities during vehicle operation. Electrical qualification methodologies are therefore commonly used to evaluate whether electronic assemblies can maintain stable electrical functionality without unacceptable degradation under rep-

representative electrical stress exposure conditions.

Electromagnetic compatibility (EMC) validation is based on the principle that electronic systems must maintain operational stability under electromagnetic disturbance conditions while simultaneously limiting undesirable electromagnetic emissions. In highly interconnected automotive electronic architectures, electromagnetic susceptibility may influence signal stability, communication reliability, and system-level functional behavior. EMC qualification methodologies therefore commonly evaluate both electromagnetic immunity characteristics and electromagnetic emission behavior under representative operating conditions[3].

Although individual validation categories focus on different degradation phenomena, automotive robustness qualification is generally based on the assumption that degradation mechanisms may interact under combined stress exposure during long-term vehicle operation. Consequently, automotive validation frameworks typically combine environmental, mechanical, electrical, and electromagnetic qualification methodologies in order to achieve broader robustness characterization and improved confidence in long-term operational reliability.

Table 2.3: Validation Categories and Associated Degradation Mechanisms

Validation Category	Representative Stress Exposure	Associated Degradation Mechanisms
ENV	Thermal, humidity and chemical exposure	Corrosion, thermomechanical fatigue
Mechanical validation	Vibration and shock loading	Solder fatigue, connector degradation
Electrical robustness	Voltage and transient stress	Electrical overstress degradation
EMC validation	Electromagnetic disturbance	Signal instability and EMC susceptibility

3

Methods

This chapter describes the research methodology and its development throughout the study. It first introduces the industrial data infrastructure and the original workflow developed for identifying high-reliability ECUs. The practical challenges encountered during implementation are then discussed, leading to the development of an alternative screening strategy. Finally, the hardware investigation of the selected ECUs is presented.

Before detailing the data extraction process, it is essential to define the vehicle scope of the CMA platform used in this research, which specifically includes Type 26 (Polestar 2) and Type 27 (XC-EX40 and EC40). This selection serves as a fixed project mandate.

3.1 Data Infrastructure

3.1.1 KDP Engineering Database

The KDP Engineering Database (KDP) is a core internal engineering information system at Volvo Cars, serving as a central repository for product definition and engineering master data across the vehicle development lifecycle. KDP plays a fundamental role in structuring, maintaining, and distributing authoritative product information, and it acts as a primary reference for multiple downstream systems within the enterprise landscape.

At its core, KDP manages vehicle, system, and component structures, including hierarchical product breakdowns and configuration relationships. Central to this capability is the Bill of Materials (BOM), which defines the physical composition of the vehicle by specifying which components are installed, how they are structured, and how they collectively realize the engineered system architecture. These structures form the basis for how vehicles are defined from an engineering perspective, linking complete vehicles to systems, subsystems, and individual components such as ECUs. By maintaining this structured BOM representation, KDP ensures consistency in how products are described and referenced across engineering, manufacturing, and quality-related functions.

Beyond structural definitions, KDP functions as a single source of truth for engineering-related master data. Information created and maintained in KDP is not intended for analytical evaluation of vehicle performance, but instead represents the designed and released product definition. As such, KDP data reflects engineering intent rather than operational behavior. This distinction is essential when combining engineering

data with field-related datasets for quality and reliability analysis.

In the broader enterprise system architecture, KDP acts as an upstream data provider. Product and configuration information defined in KDP is distributed to multiple downstream systems that rely on accurate and stable product definitions, including systems supporting manufacturing planning, diagnostics, quality follow-up, and field data analytics. As a result, KDP does not contain field performance or warranty information itself, but it enables such analyses by providing the contextual framework necessary to interpret downstream data correctly.



Figure 3.1: Login interface

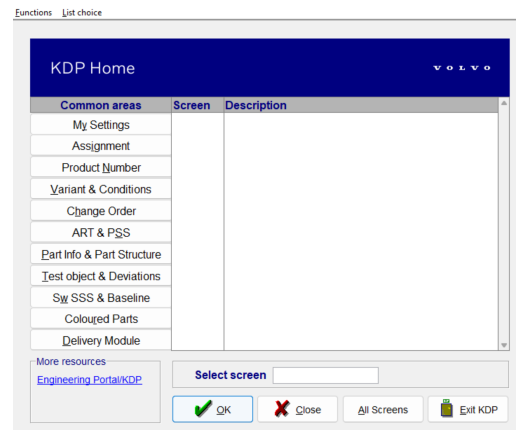


Figure 3.2: Main navigation

In the context of this research, the following subsections describe the two primary screens utilized within the KDP environment to identify, scope, and validate ECU configurations for this study.

3.1.1.1 Software Manufacturing List: Scoping and Extraction

The SW Manufacturing List(SML) serves as a key data extraction interface within KDP for establishing the study’s initial component scope. Specifically, this screen is used to generate comprehensive part number lists by applying multi-dimensional filters, including vehicle type, production timeframes (Search Time), and ECU identifiers. By defining these parameters, the SML function consolidates released engineering data into a structured format—typically exported as an Excel-based manufacturing list, which provides the essential raw input for subsequent part number scoping. This automated extraction process is critical for ensuring broad and systematic coverage of ECU-related component variants relevant to a specific vehicle platform and time window. “Prel” indicates that associated change orders are still ongoing and have not yet been released into production, so Prel = No.

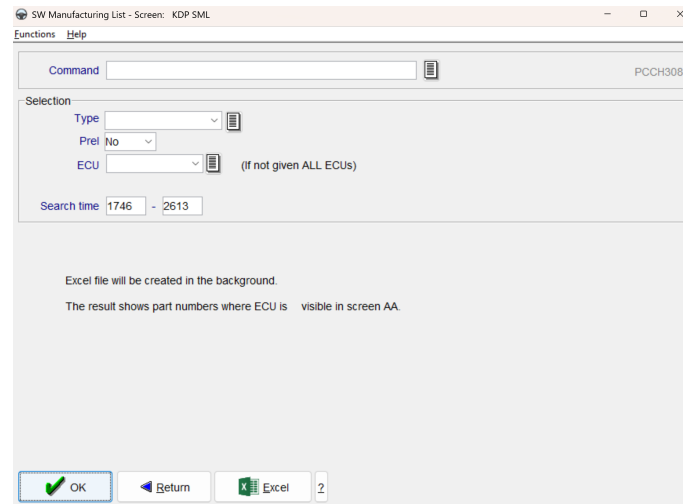


Figure 3.3: SML screen

3.1.1.2 Part Number Information: Detailed Component Inspection

While the SML interface is used for broad data extraction, the Part Number Information view (Screen AA) is primarily used after a specific part number has been identified, serving as a detailed reference for inspecting and understanding the engineering definition of a component. By entering a known part number, this screen provides comprehensive information regarding its validity, ECU association, lifecycle status, and other engineering attributes, enabling an in-depth review of the part. In the context of this study, Screen AA functions as a critical validation tool, allowing for the precise verification of an ECU's technical specifications and version history before it is selected for further reliability analysis.

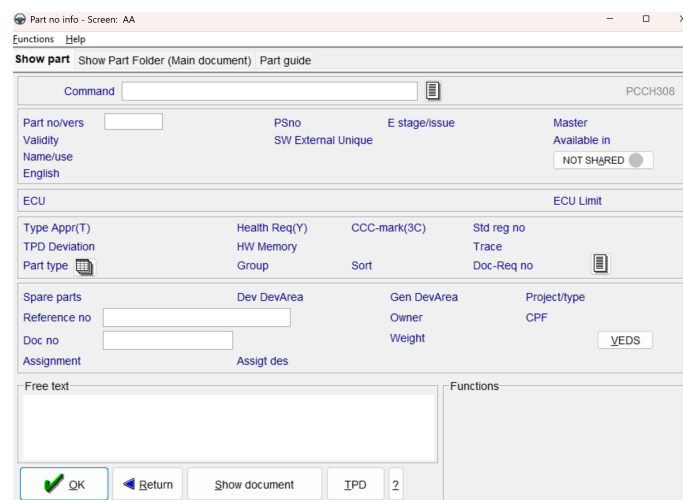


Figure 3.4: Part Number Information: screen AA

3.1.2 Field Performance Monitor: Early Warning System

3.1.2.1 Early Warning System

The Early Warning System (EWS), is a web-based analytics and reporting interface at Volvo Cars used to monitor field-related quality performance after vehicle delivery. It allows users to filter quality signals across multiple dimensions, including vehicle platform (e.g., CMA), region, and production year. It serves as a key front-end tool that aggregates and visualizes large volumes of global repair and warranty data, providing engineering and quality teams with a high-level overview of component behavior in real-world customer usage.

From a system architecture perspective, EWS functions as a presentation and analytics layer rather than a data-originating system. It does not generate or store raw field data itself; instead, it retrieves and visualizes structured quality and warranty information originating from underlying enterprise data domains. Through standardized reports and interactive views, EWS supports early identification of abnormal trends, recurring issues, and cost-relevant quality deviations across vehicles, components, and production periods.

In contrast to engineering definition systems such as KDP, which describe the intended product structure and configuration, EWS reflects actual product behavior observed in the field. The information presented in EWS represents aggregated observations from the vehicle population, including repair frequency and warranty impact, rather than controlled test results or engineering intent.

Within the context of this thesis, EWS is used as the primary access point for field-derived quality data related to ECUs.

Figure 3.5: EWS web interface for warranty repair and cost analysis

3.1.2.2 The QFU Database & Snowflake

The Quality Follow-Up (QFU) data domain represents the underlying enterprise data layer that stores and structures field-derived warranty and repair information at Volvo Cars. While EWS provides the analytical interface, the actual granular field data is maintained within QFU, which is implemented on the corporate Snowflake data platform. Within the QFU application layer, two core granular data views—`V_TPL_JOB` and `V_TPL_VEHICLE`—are utilized to provide the necessary data for identifying and quantifying the reliability of ECUs.

A. `V_TPL_JOB`: Repair Event and Component Data

The view `V_TPL_JOB` contains comprehensive job-level information related to warranty and service repairs performed on vehicles in the field. Each record represents an individual repair job and is uniquely identified by a job key, capturing the operational, technical, and transactional details associated with a specific service event. As such, this view serves as the primary source of observed repair activity and acts as the main provider of empirical “failure signals” within the scope of this study.

In addition to repair identifiers and timestamps, `V_TPL_JOB` includes detailed information on the main repair operation, associated failing components, functional group classifications, claim characteristics, and repair outcomes. Cost-related attributes (e.g., labor, material, and total repair cost) and processing status fields further support analytical assessments of repair frequency, severity, and operational relevance. By linking each repair job to a corresponding vehicle identifier, `V_TPL_JOB` enables downstream integration with vehicle-level context while preserving the repair event as the fundamental unit of analysis in reliability evaluation.

B. `V_TPL_VEHICLE`: Vehicle-Level Context

Complementing the repair-level information captured in `V_TPL_JOB`, `V_TPL_VEHICLE` provides vehicle-level attributes and configuration metadata associated with the vehicles on which repair events occur. Rather than representing a complete vehicle population registry, this view serves as a descriptive context table, supplying key characteristics—such as platform, vehicle family, model year, market, and powertrain configuration—that enable stratification and segmentation of repair analyses. From an analytical perspective, `V_TPL_JOB` and `V_TPL_VEHICLE` are linked through vehicle identifiers, enabling repair events to be evaluated within their correct product and population context.

C. Technical Implementation

To ensure the integrity and traceability of the data extraction process, the analytical environment is configured within the Snowflake platform using a series of administrative and exploratory SQL commands.

These SQL commands below configure the active Snowflake computing environment and perform a structural inspection of the `V_TPL_JOB` and `V_TPL_VEHICLE` views to verify their metadata and schema definitions before data extraction:

```
USE WAREHOUSE PROD_QI_ANALYST_QFU_WHS ;
USE DATABASE PROD_QI_DB ;
USE SCHEMA QFU_APP ;
DESCRIBE VIEW PROD_QI_DB.QFU_APP.V_TPL_JOB ;
DESCRIBE VIEW PROD_QI_DB.QFU_APP.V_TPL_VEHICLE ;
```

Listing 3.1: Snowflake environment configuration and view inspection

3.1.3 Deployment and Volume Context: Procurement Data

The final component of the multi-source data infrastructure comprises deployment and volume records maintained by the Procurement Department. Within the context of this research, exposure is defined by the volume of article numbers procured for vehicle production within the relevant platform scope. Notably, rather than representing a direct count of in-service components, these records provide an indirect

but systematic measure of component deployment at scale.

Key attributes include:

- **Article and Source Metadata:** Precise mapping of part numbers to their descriptions, supplier names, and partner codes, ensuring full traceability of hardware origins.
- **Spatio-temporal Granularity:** Production volumes are indexed by Structure Weeks, allowing the research to contextualize failure events within specific production windows and market exposure durations.

From a reliability engineering perspective, procurement data acts as the critical denominator in the failure rate equation. While the QFU database captures the “numerator” (the repair events), procurement records define the total population at risk. Relying solely on repair frequencies without this volume context would preclude statistically significant conclusions.

3.2 Identification and Scoping of ECU Population

The first stage of the methodology involves defining a comprehensive and accurate list of ECUs specifically associated with the CMA platform. This process requires consolidating engineering data from the KDP and validating it against actual volume details from the Procurement department.

3.2.1 Data Extraction from KDP and the “Part Type K” Criterion

The initial dataset, representing the theoretical E/E architecture of the platform, was extracted from KDP in the form of SML. This extraction covered the primary vehicle models within the CMA scope—Type 26 and Type 27—and the resulting records were exported into Excel format to serve as the foundation for subsequent analysis.

A critical step in this extraction was the filtering of components based on the “Part Type” attribute. Based on expert consultation with the KDP department, a specific filter was applied to select only parts where the Part Type begins with the letter “K”. The rationale for this technical criterion is as follows:

- **Part Type “K”:** Specifically designates embedded systems and Electronic Control Units (ECUs) within Volvo’s engineering nomenclature.
- **Exclusions:** Other prefixes often represent purely mechanical hardware, wiring harnesses, or standalone software versions that do not house the physical PCB-based intelligence required for this study.

Type : 27			
Time : 1746 - 2613			
Prel : N			
DateTime: 2026-03-23 10:34			
ECU : ALL			
Type	Part Type	Part Description	ECU
	>>>>	ACTIVE SAFETY DOMAIN MASTER	ASDM
27	K	CONTROL UNIT/ASDM	ASDM
27	HWSD	PRINTED CIRCUIT BOARD/ASDM	ASDM
27	SXBL	PRIMARY BOOTLOADER/ASDM	ASDM
27	SXDI	DIAGNOSTIC/ASDM	ASDM
27	SWLM	LOAD MODULE/ASDM	ASDM
27	SXDI	DIAGNOSTIC/ASDM	ASDM
27	SWL2	LOAD MODULE/ASDM	ASDM
27	SWL3	LOAD MODULE/ASDM	ASDM

Figure 3.6: Excerpt of a KDP-generated Excel output showing ECU-related part definitions and software components

By taking the union of the “K-type” parts from both the Type 26 and Type 27 datasets using Python, a consolidated master list—hereafter referred to as the *CMA_Manufacturing_List* was generated, containing an initial total 957 unique part numbers.

3.2.2 Alignment with Procurement Records

To ensure that the research focuses only on components that were actually manufactured and delivered to customers, the *CMA_Manufacturing_List* was cross-referenced with the Procurement Department’s *Volume_details_CMA* dataset. This was executed through an Inner Join operation using the Part Number as the primary key.

The population of components was subsequently refined from 957 to 939 unique parts. This reduction of 18 parts is attributed to several engineering realities:

- Prototyping and Testing: Some part numbers recorded in KDP represent experimental or test-bench units used during the development phase that never entered mass production for the CMA fleet.
- Service Parts and Accessories: Certain parts may be listed in engineering portals but lack corresponding sales or procurement volume because they are intended for specific aftermarket niche applications or were superseded before the vehicle’s Start of Production (SOP).

The resulting 939 part numbers constitute the Active ECU Population, representing the baseline for the subsequent field reliability analysis.

3.3 Extraction of Field Failure Records from QFU

The next phase of the methodology involves retrieving the actual service history for the ECUs. This process focuses on extracting raw repair records from the QFU database to identify which part numbers have encountered failures in the field and to determine their respective repair times. The objective is to establish a high-confidence dataset of hardware-related service actions that occurred after the vehicles were delivered to customers.

3.3.1 Data Environment and Connectivity

The data extraction for this stage was performed using Snowflake, which is the standardized cloud-based data warehouse for Volvo Cars' quality analysis. All repair records were retrieved from the production environment database, specifically the `PROD_QI_DB` within the `QFU_APP` schema. This setup ensures that the study utilizes the most current and official field data, consistent with the company's internal quality monitoring standards.

3.3.2 Scope Narrowing: Identifying CMA Target Models

To ensure the accuracy of the repair counts, it was necessary to link the ECU part numbers to a specific and controlled group of vehicles. Using the `V_TPL_VEHICLE` table in QFU, a filtering logic was applied to isolate the target population:

- Platform Level: The query first restricted all data to the CMA platform (`VEHICLE_PLATFORM = 'CMA'`).
- Model Level: To strictly follow the research scope, keyword-based filters were used to select specific vehicle families. This included Polestar 2 (CMA), XC-EX40, and EC40.

This dual-layer filtering ensures that any repair record identified in the next step is definitely associated with the intended vehicle architecture, preventing data from other Volvo platforms from interfering with the results.

3.3.3 Data Cleansing and Noise Reduction

To consolidate the dataset, a multi-stage SQL logic was implemented for data integration and cleansing:

- Relational Data Integration (The JOIN Logic): The core of the extraction relies on joining the filtered vehicle population (`V_TPL_VEHICLE`) with the comprehensive service record table (`V_TPL_JOB`). By using the `VEHICLE_ID` as the unique relational key, the query ensures that only repair jobs belonging to the predefined CMA fleet are retrieved. This integration is essential for isolating platform-specific performance from the massive global service database.
- Filtering Non-Technical Claims: A strict filter was applied to exclude records where the `FAILING_PART_NO` was empty or recorded as `'0'`. In automotive retail systems, many job cards are generated for non-repair activities such as general inspections, administrative corrections. Excluding these “zero-part” entries ensures that our dataset only reflects instances where a physical ECU was identified as faulty and replaced.
- Event-Based Aggregation: To avoid overcounting, the study utilized a `COUNT(DISTINCT JOB_ID)` approach. A single service visit might generate multiple data rows due to various internal system codes, but it represents only one failure event. This distinct count ensures that the final tally reflects the actual number of unique repair jobs rather than the total number of database entries.

3.3.4 Data Integration and Final Repair Count Consolidation

The extraction logic described in the previous section was implemented through SQL queries within the Snowflake environment to retrieve the raw repair data.

Following the execution of the SQL scripts for both Type 26 and Type 27 models, the resulting datasets were exported to Excel format.

PART_NO	PART_DESC	MAIN_OPERATION_NO	MAIN_OPERATION_DESC	FUNCTION_GROUP	REPAIR_TIMES	PLATFORM
---------	-----------	-------------------	---------------------	----------------	--------------	----------

Figure 3.7: Excerpt of the data schema for individual ECU part numbers and their associated repair frequencies

The resulting datasets were subsequently processed using Python to perform the final consolidation through a three-step workflow:

1. Intersection with Active Population: The raw lists from QFU (both Type 26 and Type 27) were cross-referenced with the 939 active ECU part numbers identified in Section 3.1. This intersection ensures that only components within the defined research scope are analyzed, filtering out irrelevant service data.
2. Union and Summation: The datasets for Type 26 and Type 27 after step 1 were merged using a union-all logic. For part numbers that appeared in both vehicle types, their respective `REPAIR_TIMES` were summed to represent the total field failure count across the entire CMA platform.
3. Final Classification:
 - EWS Population (264 PNs): A total of 264 part numbers were found to have at least one valid repair record, forming the basis for subsequent failure rate calculations.
 - Non-EWS Population (675 PNs): The remaining 675 part numbers showed zero hardware-related repairs in the QFU system within the observed timeframe.

This consolidated dataset, combining the theoretical population with actual field performance, establishes the quantitative foundation for the subsequent reliability analysis.

3.4 Clustering of Part Families via Change Orders

3.4.1 The Rationale for Part Number Consolidation

In the automotive industry, an ECU is rarely represented by a single, static part number throughout the entire lifecycle of a vehicle platform; instead, continuous engineering improvements, supplier optimizations, and different vehicle or configuration variants often lead to multiple iterations of the same component, each assigned a unique Part Number. Analyzing these fragmented part numbers in isolation poses a risk of statistical dilution, undermining the statistical power of the reliability assessment. Furthermore, since successor part numbers are designed to maintain the

same functional and physical position within the vehicle’s E/E architecture, treating them as unrelated entities would ignore their evolutionary continuity and result in an incomplete evaluation of the component’s true field performance.

Consequently, it is essential to cluster these individual part numbers into “Part Families” to ensure that the calculated failure rates reflect the aggregate performance of an ECU design rather than the transient lifecycle of a specific version.

3.4.2 Technical Implementation of the Selection

To operationalize the concept of Part Families, it is first necessary to clarify the relationship between Part Numbers and Change Orders. In the automotive industry, a single ECU design often undergoes multiple incremental modifications, such as component substitutions or software updates. These changes result in the issuance of new PNs, leading to the fragmentation of what is effectively a single, evolving design.

In this context, while a PN identifies a specific released instance of a component, a Change Order(CO) provides the engineering traceability for these modifications. Importantly, as a design evolves through a series of updates, it is often assigned a “CO Latest” identifier in the engineering database, which acts as the terminal link for that specific component generation. By grouping individual PNs based on this shared CO identifier, we can aggregate design evolution into higher-level “Part Families”, grouping associated Part Numbers into unified evolutionary entities rather than treating each PN as an entirely independent product.

The process was executed using the `pandas` library to ensure data consistency and scalability. For both EWS and non-EWS datasets, the pipeline first identified all time-series volume columns while excluding descriptive metadata (such as PNs, PSS, and descriptions). After cleaning the data to ensure numerical integrity, a `groupby` and `transform` operation was applied to the `CO Latest` column. This step effectively summed the individual purchasing volumes of all sub-parts within a family to calculate the `Family_Total_Volume`.

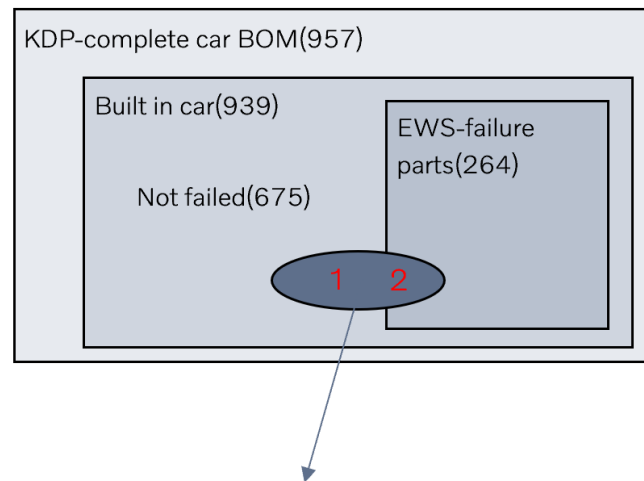
In the EWS group, this automated aggregation allowed for a more robust reliability calculation. By consolidating fragmented volumes at the family level, the repair counts could be normalized against the aggregate market exposure, thereby preventing the statistical bias that often arises when analyzing specific part iterations in isolation.

For the non-EWS group, the pipeline further implemented a ranking logic. After summing the volumes by CO, the dataset was sorted in descending order to isolate the “silent success stories”—components that have demonstrated zero field failures despite substantial production volumes.

3.5 Methodological Reflection and Adaptation

After finishing the screening framework through the steps detailed in Sections 3.2 to 3.4, it seems like I have built a logically structured approach. On paper, the selection process appears straightforward: isolating components with the lowest repair-to-volume ratios in the EWS group and ranking the highest-volume performers in the

non-EWS group (see Figure 3.8). However, as the analysis progressed, two major issues began to emerge, causing me to question the robustness of the results.



What we want: top volume and less repair-to-volume ratios

Figure 3.8: Concept of part selection

First, I have a concern about the aggregation logic used to construct the Part Families. As mentioned before, a single ECU design continuously undergoes incremental modifications, meaning that different iterations within the same family may possess slight variations in their PCB layouts or component suppliers. Since the primary goal is to identify inherently superior designs, I question whether grouping these distinct iterations together compromises the initial intent. By normalizing the aggregate repair counts against the total family volume, the resulting average failure rate risks masking the exceptional performance of a specific, high-quality iteration, or conversely, diluting the flaws of a weaker one. Internal discussions at Volvo indicated that identifying reliability at the component/family level is the primary strategic priority, with the option for granular analysis later. I remained skeptical about this at that time.

The second issue emerges from a broader view of the processed data, which raises questions regarding database completeness. Out of the 939 ECUs investigated, the vast majority have no repair records whatsoever. Most notably, within the non-EWS group, the top-ranked ECU family exhibits an aggregate volume exceeding 2 million units with zero recorded field failures (as detailed in the *CMA_non_EWS_Volume_CO_Family_Ranked* dataset). From an engineering standpoint, it is highly improbable for a component with such extensive market exposure to maintain absolute perfection. This contrast strongly suggests a “reality gap” between actual field events and how claims are captured in the QFU database. Consequently, these “zero-failure” results must be interpreted with caution, as the high ranking of these families may be heavily influenced by data-reporting limitations rather than reflecting flawless hardware reliability alone.

To investigate the root cause of this massive “zero-failure” problem, I consulted with the Current Model Quality (CMQ) and Product Lifecycle Management (PLM) departments. Through discussions, I discovered a critical data logging issue rooted in

the use of Exchange Numbers. According to Volvo’s official documentation, when a vehicle is serviced, an Exchange Number is used to identify the replacement part provided for the service action. In a proper data logging scenario, the database should record the original, broken part under the “Failing Part Number” field. However, in reality, workshop technicians frequently logged the Exchange Number of the newly installed part into the “Failing Part Number” field instead. Consequently, many actual production Part Numbers appeared to have zero repair records simply because their failures were recorded under these service-specific Exchange Numbers.

This logging error created a major roadblock for the screening framework. To continue with this approach, it would be necessary to cross-reference and reconstruct a complete mapping matrix between the actual production PNs and their corresponding Exchange Numbers.

Upon further investigation, I found that this exchange part information is documented as constituent parts within the KDP engineering system; when querying a specific PN, the system displays its associated Exchange Number. However, on an enterprise or database level, there was no centralized, structured database that stored this mapping relationship systematically.

Because building such a global mapping table from scratch without a centralized database was not viable within the scope of this project, I realized that continuing down this path was impractical. Therefore, instead of trying to force a technical fix for this mapping issue, I decided to step back and find an alternative solution to screen for high-reliability ECUs without relying on this contaminated field repair data, meanwhile the first concern is naturally resolved.

3.6 Alternative Screening Strategy: Targeted Investigation via EWS Web Portal

This adaptation improved the interpretability of the screening result, even though it reduced automation and introduced manual verification effort.

3.6.1 Initial Candidate Identification via Production Volume

Having abandoned the contaminated QFU database, I shifted to a more targeted methodology. Although the repair records in the database were skewed by the logging issue, the aggregate production volumes calculated earlier remained highly valuable. Therefore, I utilized the sorted “Top Volume” list as the foundation for this new framework. By focusing on the ECUs with the highest market exposure, specifically those with aggregate production volumes exceeding approximately one million units—such as CONTROL UNIT VGM, CONTROL UNIT TCAM, CONTROL UNIT ECM, and CONTROL UNIT ASDM—I established a robust primary candidate pool. The objective was then to determine the true repair frequencies for these specific high-volume components.

3.6.2 Manual Inspection via the EWS Portal

To obtain accurate repair data without relying solely on database records affected by the previously identified logging limitations, I redirected my focus to the EWS Web Portal (see Figure 1.5). Unlike the raw database, the web portal provides detailed, human-readable descriptions of the main operations performed during each service action. So we can systematically query the top-ranking ECUs from the candidate pool through this portal to manually extract their respective repair times.

3.6.2.1 Engineering Categorization of Failure Signals

A critical step in this manual extraction process was defining what constitutes a genuine hardware failure. The portal logs various service actions for a single ECU, which necessitated strict engineering categorization to separate hardware degradation from software maintenance.

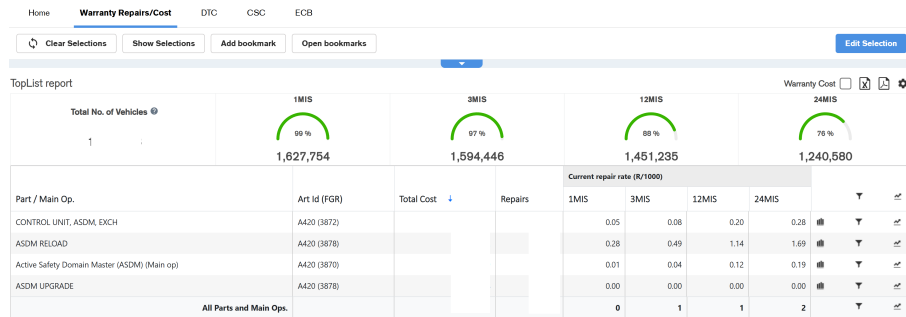


Figure 3.9: Operation-level segmentation of ASDM repair data

Taking the Active Safety Domain Module (ASDM) as a representative example (see Figure 3.9), the EWS web portal displays multiple distinct sub-categories under the same component name. These entries include software reloads, version upgrades, and generic main operations alongside actual hardware exchanges. If all these service events were counted indiscriminately as failures, the reliability analysis would be heavily distorted by routine software adjustments. To prevent this, the following specific boundaries were established to isolate true hardware failure signals:

- **Hardware Replacements (Valid Failure Signals):** Only service events explicitly marked with the operation "EXCH" (e.g., CONTROL UNIT, ASDM, EXCH) were counted as valid repair times. This indicates that the ECU hardware physically failed and was consequently replaced with an exchange part.
- **Software and General Operations (Excluded):** Service actions labeled as "RELOAD" (reprogramming or re-flashing the existing ECU software without replacing the hardware) and "UPGRADE" (updating the ECU software to a newer or improved version) were strictly excluded. Similarly, generic labor or diagnostic entries without physical component replacement (such as ASDM (Main op)) were also filtered out. These represent routine maintenance or software modifications rather than physical hardware unreliability.

3.6.2.2 Formulation of the Final Screening Metric

With the hardware-related repair cases successfully isolated from software-related operations in Section 3.5.2.1, the next step was to establish a quantitative metric capable of comparing reliability performance across different ECU populations. Direct comparison based solely on hardware repair counts was considered insufficient, since ECU families with larger deployment volumes naturally have more opportunities to generate repair records. Therefore, repair occurrence was interpreted together with market exposure.

In this study, production volume was used as a practical approximation of the population at risk, while EXCH-related repair occurrence was used as the closest available indicator of hardware repair events. Based on this assumption, ECU families exhibiting both high deployment exposure and low hardware repair occurrence were considered candidates for further investigation.

To support this comparison, an Adjusted Hardware Repair Rate was formulated by normalizing the verified hardware exchange counts against the aggregate market exposure, as shown in the following equation:

$$\text{Repair Rate} = \frac{\text{Total EXCH Repairs}}{\text{Family Total Volume}} \quad (3.1)$$

By applying this formula to the primary candidate pool, the statistical distortion caused by the “Exchange Number” logging error was completely bypassed.

3.6.3 Selection Guidelines for Specific PNs

Although the framework in Section 3.5.2 successfully identified the top-performing ECU families, it raised a new practical question. An ECU family is not a single, specific component; instead, it consists of a group of different part numbers introduced over the years. Since the next step required a deep-dive analysis, it was not practical to study the entire ECU family. Therefore, a single specific PN was selected for further investigation. To guide this choice, we held an internal discussions and established two general rules based on the information in the *Volume_details_CMA* dataset:

- **High Volume Share:** The chosen PN should account for as much of the total family volume as possible. It must be a standard, mass-produced part rather than a low-volume variant. Choosing a high-volume PN ensures that the component has sufficient market exposure to be truly representative of that family.
- **Production Recency and Improvement:** By manually looking up PNs in the *Volume_details_CMA* dataset, I prioritized parts that have been heavily produced in recent years. The engineering logic here is that as an ECU design undergoes modifications over time, the newer hardware iterations are generally expected to become better and more reliable. Therefore, selecting a recent, high-volume PN ensures that the study focuses on the most mature and updated version of the design.

3.7 Hardware-oriented engineering investigation

Following the data-driven identification of high-reliability ECU populations, an additional hardware-oriented investigation was conducted on a limited number of selected ECU samples. The purpose of this stage was not to perform a full electrical redesign analysis or detailed failure mechanism investigation, but rather to identify recurring engineering and manufacturing characteristics that could potentially contribute to long-term field robustness.

The investigation combined two complementary activities:

- physical inspection of ECU hardware and PCBs,
- and a targeted review of available DV and PV documentation.

The assessment was primarily qualitative and comparative in nature. Focus was placed on visible engineering practices, manufacturing quality indicators, environmental protection measures, and the scope of validation activities associated with the selected ECUs.

3.7.1 Physical Inspection and Open-Lid Assessment

A qualitative open-lid inspection was conducted on the selected ECU samples in order to observe visible hardware characteristics potentially associated with long-term robustness in automotive operating environments. The investigation focused primarily on observable engineering and manufacturing features rather than detailed electrical or mechanical analysis.

The assessment included a comparative visual review of ECU housings, connector regions, and PCB assemblies using both physical samples and high-resolution PCB images. Attention was generally given to visible aspects related to manufacturing consistency, soldering quality, PCB cleanliness, connector integration, and overall layout organization.

In addition, the inspection considered the presence of environmental protection measures commonly used in automotive electronics, including conformal coating, sealing structures, and other visible protective materials applied around sensitive areas or connector interfaces.

The investigation remained observational and qualitative in nature. No electrical measurements, thermal characterization, signal integrity analysis, or detailed mechanical simulations were performed as part of this study. The inspected ECU samples may additionally serve as reference (“golden”) samples for future material, solder-joint, and failure-analysis activities beyond the scope of the present study.

3.7.2 Targeted Review of DV/PV Documentation

In addition to the hardware visual inspection activities, a targeted review of available DV and PV documentation is conducted, where relevant documentation can be accessed, in order to complement the comparative investigation of the selected ECU platforms.

The purpose of the documentation review is to provide contextual understanding of the engineering validation processes associated with ECU platforms demonstrating

strong field reliability performance.

Due to the varying availability, large volume, and broad technical scope of the validation material, the review is intentionally limited to selected documentation categories considered relevant to general robustness and reliability assessment. Particular attention is given to validation activities associated with environmental exposure, vibration-related testing, electrical robustness, and validation progression across different product development stages.

Where documentation is available, observations are additionally made regarding the apparent breadth and maturity of validation coverage associated with the investigated ECU platforms, including indications of recurring verification activities and structured engineering validation processes during product development.

The documentation review therefore primarily serves as a qualitative engineering reference framework supporting the broader comparative investigation of high-reliability ECU designs.

4

Results

This chapter presents the results obtained using the screening methodology proposed before. It first reports the selected high-reliability ECU families, followed by the findings from physical inspection and the review of available documentation.

4.1 Quantitative Screening and Part Number Selection Outcomes

Based on the equation 3.1 defined in Section 3.6, the initial selection phase narrowed the target population to ECU families within the CMA platform exhibiting the highest aggregate production volumes (Family Total Volume), generally around or exceeding approximately one million units.

Once this high-volume candidate pool was defined, a systematic manual query was conducted to extract the precise hardware replacement frequencies (EXCH Repairs) for each respective family. To comply with Volvo Cars' proprietary data protection protocols and safeguard commercial confidentiality, absolute production volumes and exact workshop repair counts are withheld from this text. However, the quantitative normalization revealed that the top-performing components consistently exhibited normalized repair rates within an exceptionally low magnitude of a few parts per ten-thousand (the 10^{-4} range). This minimal failure signature indicated consistently strong field robustness under diverse and unconstrained global field conditions.

The primary data parameters for these isolated top-performing ECU families are summarized in Table 4.1.

Table 4.1: Normalized Screening and Exposure Metrics for High-Reliability ECU Families

ECU Family Name	Functional Domain	Market Exposure	Exposure	Repair Rate Range (EXCH)
ASDM	Active Safety & ADAS Domain Control	> 1,500,000 units		3.0×10^{-4}
ECM	Powertrain Control	> 1,000,000 units		3.5×10^{-4}
VGM	Vehicle Network Gateway	> 1,000,000 units		$> 5.0 \times 10^{-4}$
SOD	Active Safety Sensing	$\approx 1,000,000$ units		4.0×10^{-4}

Note: Absolute production volumes and raw repair statistics are generalized into normalized ranges to preserve corporate confidentiality.

To conduct the subsequent physical and validation analysis within the scope and time limits of this thesis, three specific components were extracted from this population. Following the baseline guidelines of volume dominance and temporal recency within the *Volume details_CMA* dataset, the selection was restricted to specific mass-produced Part Numbers that represented the most updated and stable design state. Consistent with the corporate confidentiality constraints applied to the production volumes, the specific engineering Part Numbers of these selected units are withheld from this report and referenced purely by their functional component names.

The three isolated target components and their corresponding system domains are:

- Engine Control Module (ECM): Representing critical low-voltage powertrain control.
- Active Safety Domain Module (ASDM): Representing critical low-voltage active safety systems.
- Inverter: Introduced as a representative high-voltage propulsion component.

4.2 Visual Inspection (Open-Lid Assessment)

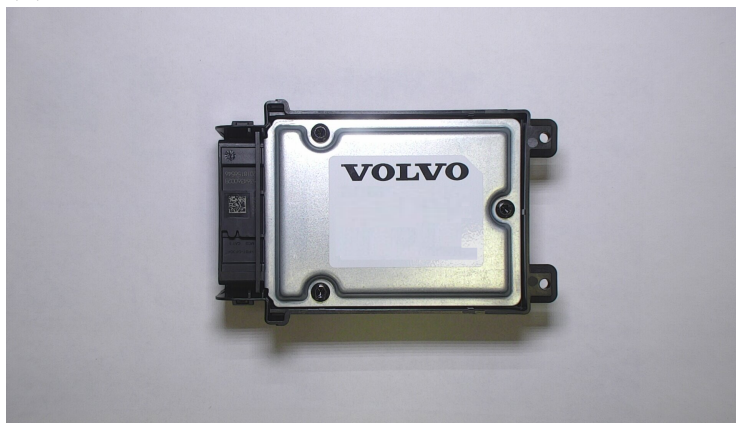
4.2.1 External Housing and Connector Observations

4.2.1.1 External Views of the Investigated ECUs

The external housing and connector configurations of the three selected ECU assemblies were documented through front, rear, and connector-side photographs. These images provide the visual basis for the subsequent housing and connector observations.



(a) Front view

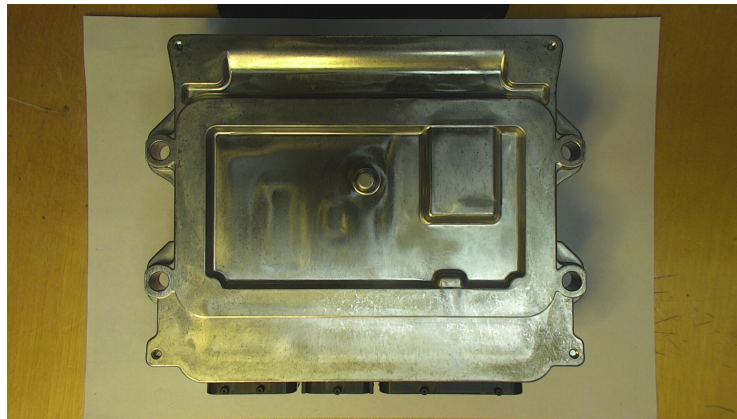


(b) Rear view

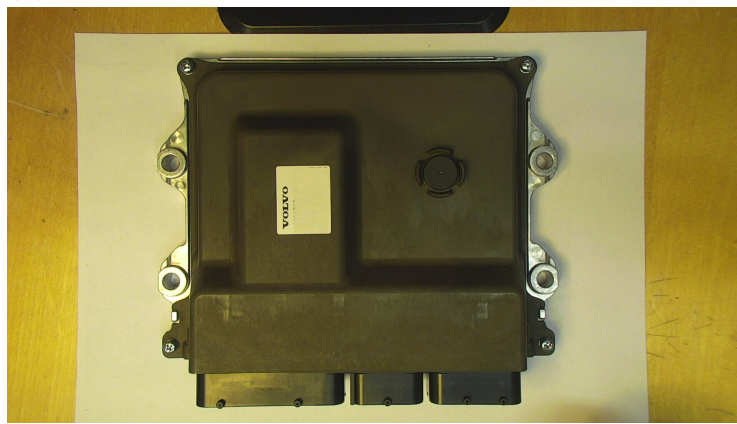


(c) Connector side

Figure 4.1: External views of the ASDM ECU assembly.



(a) Front view

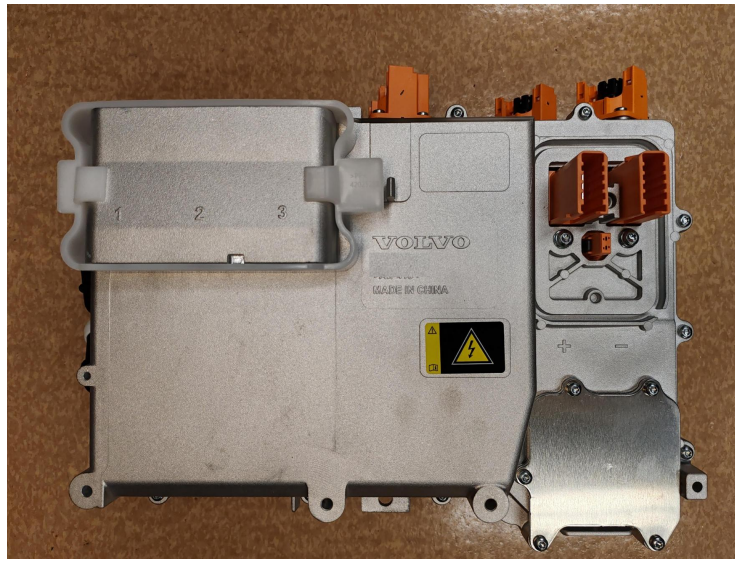


(b) Rear view



(c) Connector side

Figure 4.2: External views of the ECM ECU assembly.



(a) Front view



(b) Connector side

Figure 4.3: External views of the inverter ECU assembly.

4.2.1.2 Observation Results

Visual inspection of the investigated ECU assemblies identified several recurring external packaging characteristics associated with robustness-oriented automotive electronic design. Although the investigated units represented different functional domains within the vehicle electrical architecture, a number of common engineering observations were visually identified across the external housing and connector structures.

- **Compact enclosure geometry and minimized internal air volume**
Several enclosure geometries appeared closely adapted to the internal electronic architecture, resulting in relatively compact packaging configurations with limited unused internal air volume. In multiple assemblies, the housing structure additionally appeared locally shaped around larger internal components and mechanically significant regions. Such packaging approaches may contribute to reducing unnecessary internal moisture accumulation, limiting internal mechanical movement, and improving overall packaging stability during long-term operational exposure.

- Mechanically reinforced connector and mounting structures

The connector interfaces generally appeared mechanically integrated into the housing structures using relatively robust mounting geometries and compact interface arrangements. Large mounting points and reinforced housing fixation regions were additionally observed in several assemblies, particularly in larger powertrain-related ECUs. These structural characteristics may contribute to reducing excessive mechanical loading transfer to internal PCB assemblies during vibration and shock exposure under vehicle operating conditions.

- Environmental protection and enclosure sealing observations

In two of the investigated ECU assemblies, sealing material was visually observed along enclosure interface regions, indicating explicit consideration for environmental isolation and moisture limitation within the housing structures. Visible sealing paths and tightly integrated enclosure interfaces appeared consistent with packaging strategies intended to reduce contamination exposure and environmental interaction with internal electronic assemblies. Although no destructive sealing verification or material identification was performed, the observed sealing features suggested robustness-oriented environmental protection considerations.

- Application-oriented enclosure and connector differentiation

Differences in enclosure architecture and connector configuration were visually observed between the investigated ECU types. Smaller low-voltage assemblies utilized relatively compact polymer-based enclosure structures, while larger powertrain and propulsion-related units incorporated mechanically reinforced metallic housings and more differentiated connector interfaces. In the investigated high-voltage assembly, physically separated connector regions and clearly differentiated connector geometries were additionally observed, potentially supporting electrical isolation and interface robustness considerations associated with high-power automotive electronic systems.

4.2.2 PCB-level visual inspection

4.2.2.1 PCB-Level Views of the Investigated ECUs

Figure 4.4–Figure 4.9 present representative PCB-level inspection views of the investigated ECU assemblies after enclosure opening. The figures illustrate the general PCB layout organization, connector integration regions, fixation structures, and component distribution characteristics observed during the visual inspection activities.

To comply with corporate confidentiality requirements, identifiable hardware information including part numbers, serial identifiers, QR codes, and traceable manufacturing markings has been intentionally blurred or masked in the presented images.

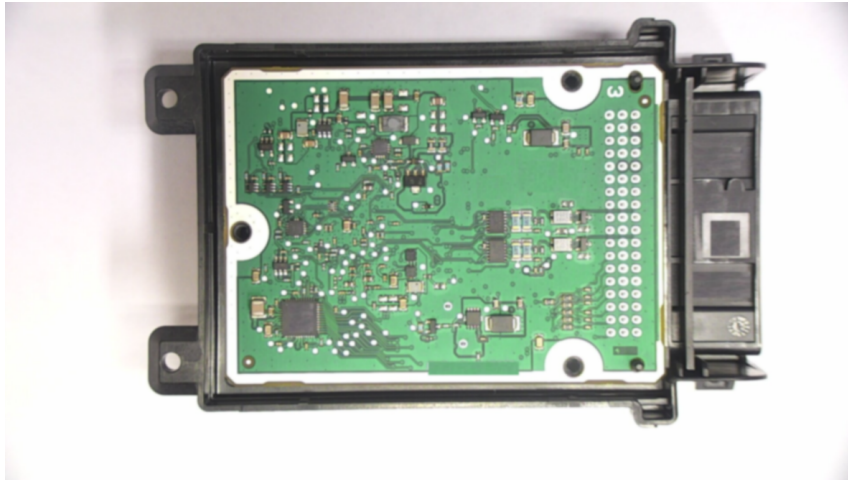


Figure 4.4: ASDM Side A

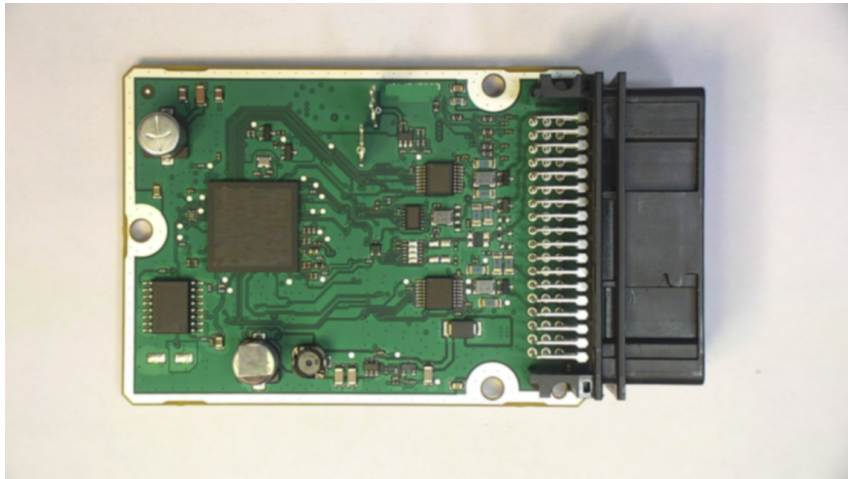


Figure 4.5: ASDM Side B

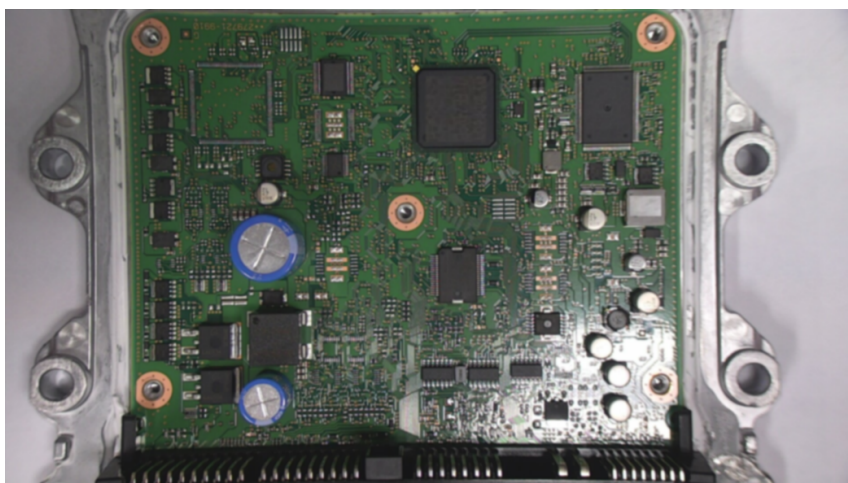


Figure 4.6: ECM (single side)

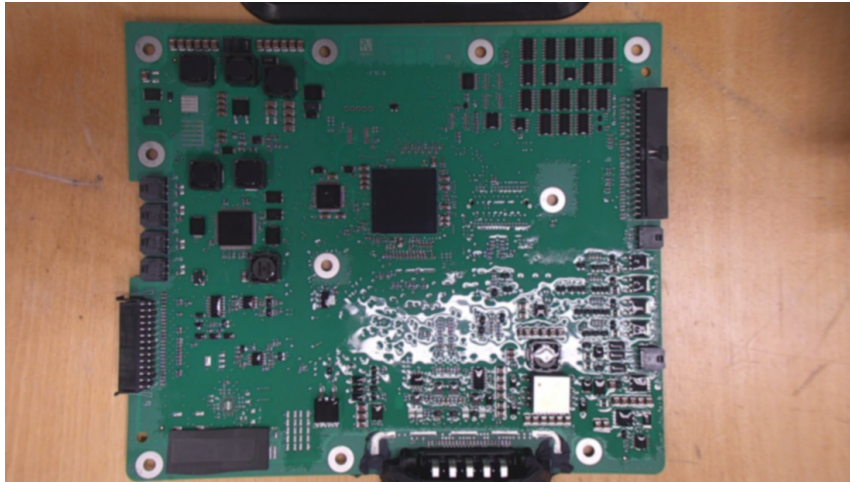


Figure 4.7: Inverter 1

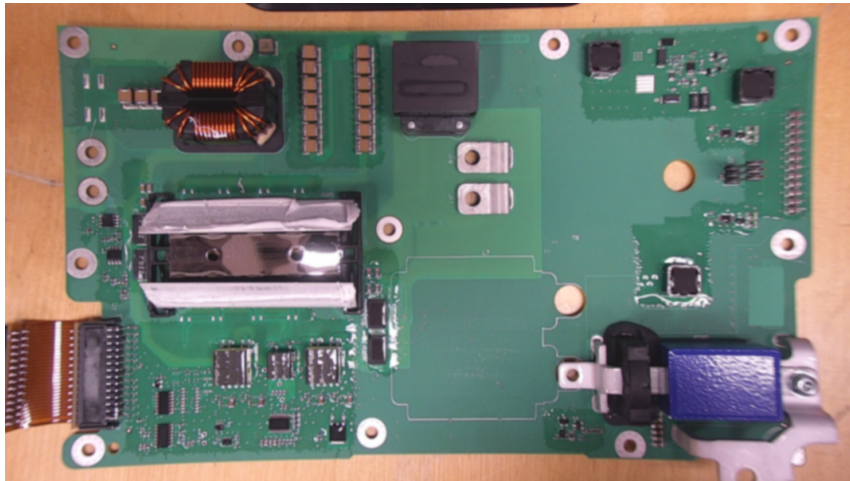


Figure 4.8: Inverter 2

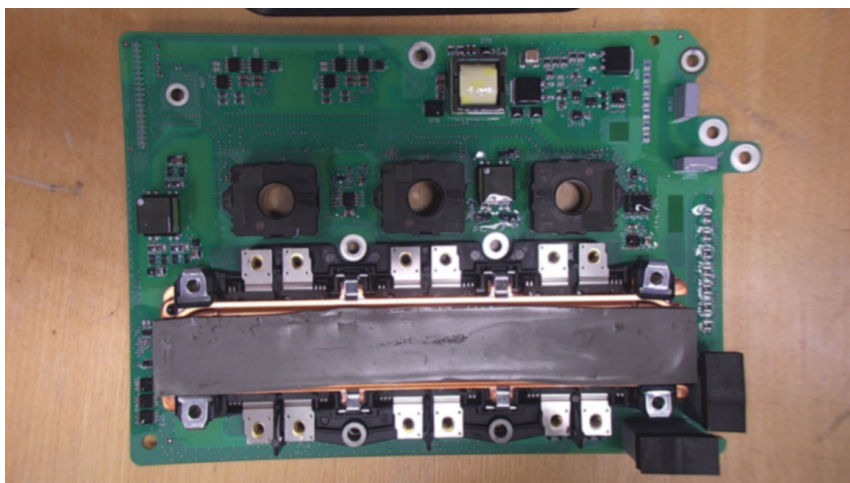


Figure 4.9: Inverter 3

4.2.2.2 Observation Results

ECU-Specific PCB Observations:

- **ASDM PCB Assembly:** The ASDM assembly exhibited a relatively compact PCB architecture with a moderate component density and a mechanically integrated connector interface. No selective soldering regions were visually identified on the inspected PCB assembly, while press-fit connector technology appeared to be utilized in the interface structure. Compared with conventional soldered interconnections, press-fit connections may reduce dependence on solder-joint integrity and eliminate several solder-related degradation mechanisms such as solder fatigue and void-related failures. In addition, no visible tin whisker formation was observed during PCB inspection. This observation is consistent with the whisker-mitigation considerations discussed in Section 2.3.2.
- **ECM PCB Assembly:** The ECM assembly showed a single-sided PCB population strategy, where the majority of electronic components were mounted on one side of the board while the bottom side was positioned directly against the metallic enclosure structure. This arrangement may provide a relatively efficient thermal conduction path between heat-generating components and the housing. No additional adhesive fixation or glue reinforcement was visually identified on larger components. Instead, the assembly appeared to rely primarily on mechanical fixation, PCB support structures, and component placement strategies to maintain mechanical stability under operational loading conditions.
- **Inverter PCB Assembly:** The inverter assembly exhibited the highest structural complexity among the investigated units. Multiple functional regions, power electronic components, and mechanically integrated subassemblies were observed within the enclosure. Visible conformal-coating-like coverage was identified on portions of the PCB surface, suggesting consideration for environmental protection against moisture and contamination exposure. In addition, the assembly architecture appeared to maintain physical separation between high-voltage and low-voltage functional regions, consistent with common automotive power electronics design practices intended to support electrical robustness and insulation performance.

Visual inspection of the investigated PCB assemblies identified several recurring layout and structural characteristics associated with robustness-oriented automotive electronic design.

- **PCB fixation and mechanical support structures**
Multiple PCB fixation points and mechanically reinforced mounting regions were observed across the investigated assemblies. In several cases, the PCB structures appeared mechanically integrated with surrounding enclosure support regions through distributed screw fixation and localized reinforcement areas. Such structural arrangements may contribute to reducing PCB deformation and limiting PCB warpage while improving board-level mechanical stability during vibration and shock exposure under vehicle operating conditions.
- **Connector-to-PCB integration and edge-supported interface regions**

The connector interfaces were generally positioned along mechanically supported PCB edge regions and appeared closely integrated with the surrounding housing structures. Connector pin regions additionally showed relatively compact interconnection layouts and localized mechanical support features. These observations may indicate consideration for reducing excessive mechanical loading transfer from external connector interfaces into unsupported PCB regions during long-term operational vibration exposure.

- PCB layout distribution characteristics

The investigated PCB assemblies did not show excessive clustering of mechanically larger components or connector-related structures within isolated board regions. In several cases, larger components, mounting points, and connector interfaces appeared relatively distributed across the PCB area rather than concentrated near a single edge or corner of the assembly. Such layout characteristics may contribute to more balanced mechanical loading conditions and reduced localized stress accumulation during vibration and thermal cycling exposure.

- Protective surface appearance and PCB cleanliness

The inverter assembly showed visible glossy surface coverage characteristics consistent with conformal coating or protective surface treatment on portions of the PCB assembly. In contrast, the remaining investigated PCB assemblies did not show visually obvious coating layers but generally appeared clean and free from significant flux residue, corrosion-related discoloration, or major contamination accumulation. Although no material verification or chemical analysis was performed, the overall PCB appearances were visually consistent with controlled assembly cleanliness and environmental protection considerations.

4.3 Engineering Validation (DV/PV) Documentation Review Findings

The inspection results presented in this section were not generated through inspections performed by the author. Instead, the observations and microscopic images were extracted from pre-existing DV/PV documentation provided by Volvo Cars. The author reviewed, consolidated, and interpreted these materials for the comparative hardware investigation presented in this thesis.

Available DV/PV documentation was reviewed to evaluate whether the selected ECU assemblies had been subjected to reliability-oriented validation activities during product development. The review focused on test evidence related to environmental tests, electrical tests, mechanical load tests, chemical load tests, life tests, and post-test physical condition.

For the reviewed validation documentation, a visual inspection was commonly performed after the tests were completed. Such post-test inspection activities were used to identify potential physical degradation. An example of the post-test visual inspection summary format is shown in Figure 4.10.

Visual inspection after test - Summary						
n°	Check item	VED #01	VED #02	VED #03	VED #04	VED #05
1	No evidence of mechanical deformation is allowed.	OK	OK	OK	OK	OK
2	No evidence of water, dust or salt intrusion inside the component is allowed.	OK	OK	OK	OK	OK
3	No evidence of whisker growth longer than 20µm is allowed.	OK	OK	OK	OK	OK
4	No evidence of electro migration or electro chemical migration is allowed.	OK	OK	OK	OK	OK
5	No evidence of corrosion products, that can be judged to affect fir or function, is allowed.	OK	OK	OK	OK	OK
6	No signs of wear, fretting related corrosion are allowed.	OK	OK	OK	OK	OK
7	No signs of wear or abrasion on wire insulation are allowed.	OK	OK	OK	OK	OK
8	No warping of printed circuit board is allowed.	OK	OK	OK	OK	OK
9	No delaminating of printed circuit board or printed circuit board tracks is allowed.	OK	OK	OK	OK	OK

Figure 4.10: Example of post-test visual inspection summary after validation exposure. Source: Internal Volvo Cars DV/PV documentation.

Across the reviewed documentation, the selected ECU assemblies generally showed compliant validation outcomes, with no major reliability-critical nonconformities reported in the inspected test results. Therefore, the DV/PV review was not treated merely as a pass/fail documentation check, but as supporting evidence for identifying which reliability-related failure mechanisms were considered and verified during development.

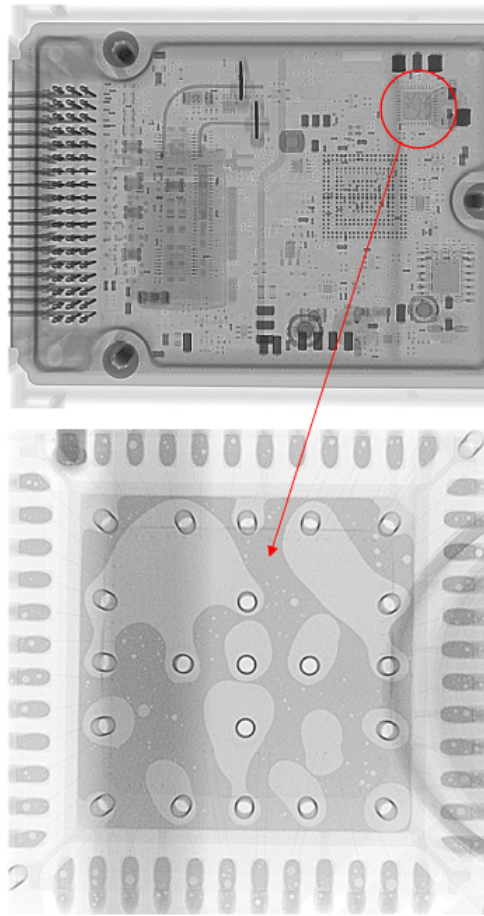
Several reliability-relevant findings were identified from the reviewed reports. These findings are summarized in the following.

The internal inspection and cross-section test report for the ASDM assembly was reviewed to evaluate post-validation physical integrity, solder-joint quality, press-fit interconnection condition, and connector-related whisker risk. The report was performed after PV test exposure on boards without coating and included external inspection, internal inspection, X-ray inspection, and cross-section analysis.

A total of 28 boards were inspected and confirmed acceptable. The reported observations included minor white oxidation inside the cover and label peeling on selected samples, both of which were assessed as having no influence on ECU performance. In addition, solder voids were observed under component U902 on all inspected boards, and one whisker was identified on connector pin No. 33. However, all reported observations remained within the specified acceptance criteria, and the inspected units were classified as conforming.

3.2 External inspection : Observation.

Figures 16: Ex. Sample Argus2 Volvo N° VV1590 Leg2



Voids under the component U902, observed on all the boards.

Figure 4.11: X-ray inspection showing solder voids under component U902. Source: Internal Volvo Cars DV/PV documentation.

X-ray solder void observation: X-ray inspection identified solder voids under component U902 on the inspected boards, as illustrated in Figure 4.11. Although voiding was observed, the report concluded that no effect on electrical or thermal conductivity was identified. This conclusion was supported by the reported thermal comparison, where the maximum measured U902 temperature under PV3 hardware testing was 116°C at an ambient temperature of 85°C, remaining below the U902 junction temperature limit of 137°C. Therefore, the observed voiding was considered acceptable within the evaluated thermal and electrical performance context.

Connector whisker observation: A whisker was observed on connector side-top pin No. 33, as shown in Figure 4.12. The measured whisker length was reported as 44 μm , which remained below the specified acceptance limit of 90 μm . Therefore, the whisker observation was classified as acceptable and did not result in non-conformity of the inspected unit.

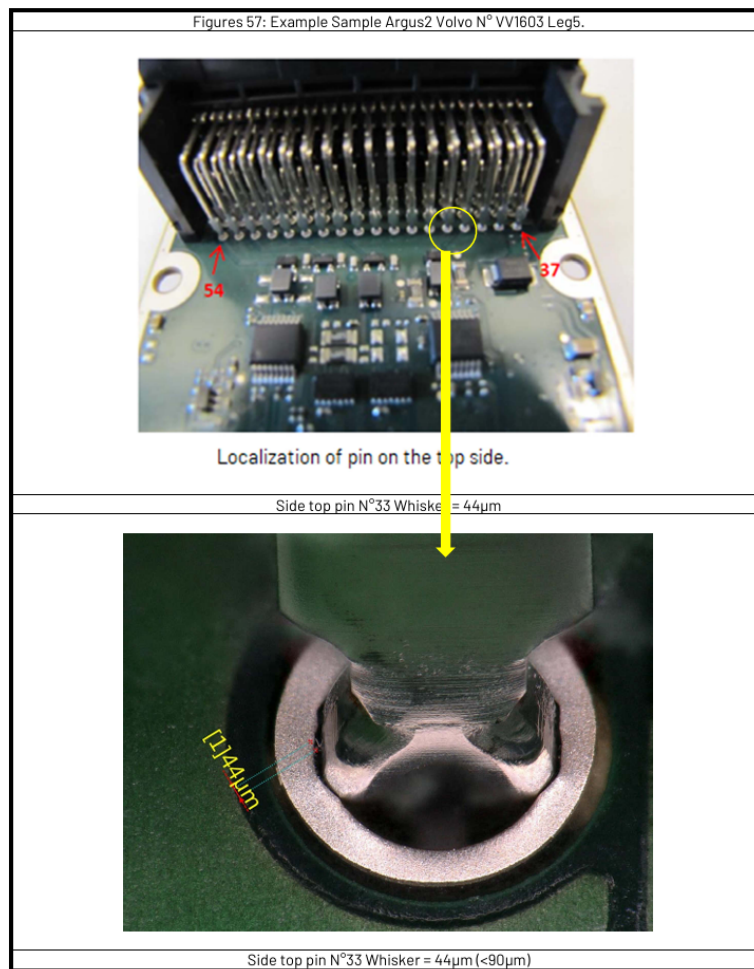


Figure 4.12: Whisker observation on connector pin No. 33. Source: Internal Volvo Cars DV/PV documentation.

4. Results

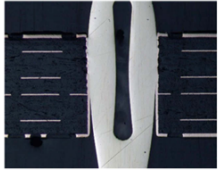
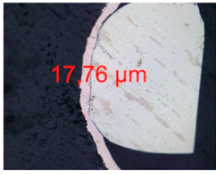
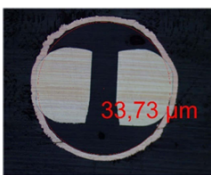
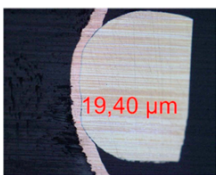
	Longitudinal Cross section	Transversal Cross section	Transversal Cross section
	2x8 pins observed	2x20 pins observed	2x20 pins observed
Norm IEC 60352-5 2012	Deformation of the inner layer (Limit<50µm)	Deformation a of the copper plating (Limit<70µm)	The residual thickness (Limit>8µm)
Veoneer E187779 005	Deformation of the inner layer (Limit<50µm) IEC requirement	Deformation a of the copper plating 0.8 mm pin - Limit<25µm 0.8 mm pin - Limit<70µm	The residual thickness (Limit>8µm)
8 Connector Board VV N°1577 (KCE) Longitudinal Board VV N°1612 (KCE) Transversal Side Top Test Mechanical Fatigue	 Low deformation.	 22,77 µm OK	 17,76 µm OK
8 Connector Board VV N°1581 (Techwise) Longitudinal Board VV N°1615 (Techwise) Transversal Side Top Life test	 26,22 µm OK	 33,73 µm OK	 19,40 µm OK

Figure 4.13: Press-fit connector cross-section analysis. Source: Internal Volvo Cars DV/PV documentation.

Press-fit cross-section analysis: Cross-section analysis was performed on press-fit connector regions to assess mechanical deformation and remaining conductive structure after test exposure. The inspected criteria included inner-layer deformation, copper plating deformation, and residual copper thickness. The reported measurements remained within the specified limits, and the inspected sections were classified as acceptable. This indicates that the press-fit interconnection did not show excessive mechanical damage or unacceptable deformation under the evaluated conditions which is consistent with the mechanical robustness considerations discussed in Section 2.3.2.

5

Conclusion and Discussion

5.1 Conclusions

This study demonstrates that industrial field operational data can be systematically utilized to identify representative ECU populations exhibiting consistently low field repair rates. By integrating engineering product definitions, production-volume information, and field repair records, the proposed workflow established a practical screening methodology capable of distinguishing genuinely reliable ECU families from products with merely limited market exposure. Although the original vision of a fully field-data-driven methodology could not be completely realized due to industrial data limitations, the study confirmed that meaningful reliability screening can still be achieved through systematic cross-referencing of heterogeneous engineering databases.

The subsequent combining of field screening and hardware-oriented validation activities provides substantially richer engineering knowledge. Across the investigated ECU families, recurring engineering characteristics were identified, including robust connector interconnection solutions such as press-fit technology, effective environmental protection strategies including sealing and conformal coating where applicable, high manufacturing quality reflected by acceptable solder-joint integrity and controlled contamination, as well as comprehensive validation evidence demonstrating satisfactory mechanical and environmental robustness. While these observations should not be interpreted as universal design requirements, they represent practical engineering characteristics consistently observed among the investigated low-repair ECU populations and may therefore provide valuable input for future reliability-oriented requirement development.

Another important conclusion of this work is that reliable engineering conclusions cannot be obtained from a single industrial database in isolation. Repair frequency alone does not adequately represent product reliability, since it is strongly influenced by production volume, service practices, and data-recording strategies. Likewise, engineering product definitions or manufacturing information alone cannot describe field performance. Meaningful reliability assessment therefore requires systematic integration of engineering, production, validation, and service-related information.

Finally, the Exchange Number traceability issue identified during this study illustrates one of the major practical challenges associated with industrial reliability analysis. The inability to establish complete traceability between original production parts and exchanged service parts prevented the originally proposed methodology from being fully implemented. Nevertheless, the study demonstrated that practi-

cal engineering screening can still be achieved by adopting an alternative workflow based on EWS web information together with engineering definitions and field repair data. This adaptation not only enabled the completion of the present study but also provides a practical reference for future industrial reliability investigations conducted under similar data availability constraints.

5.2 Discussion: Methodological Assumptions and Limitations

The findings presented in this study should be interpreted in light of several methodological assumptions that define both the applicability and the interpretation boundaries of the proposed screening methodology.

First, the methodology assumes that EXCH-related repair records provide a practical approximation of hardware replacement activity. Although an EXCH occurrence does not necessarily represent a confirmed hardware failure identified through detailed failure analysis, it constitutes the most direct and consistently available indicator of hardware-related field repair activity within the investigated industrial data environment. Consequently, the screening results should be interpreted as identifying products with favourable field repair performance rather than directly quantifying intrinsic hardware reliability.

Second, production volume is assumed to approximate field exposure. While production data cannot directly capture operating hours, environmental conditions, or customer usage profiles, it provides a practical basis for comparing repair occurrence across ECU populations with different deployment scales. Prioritising highly deployed ECU families further reduces the influence of small-sample effects, thereby increasing confidence in relative performance comparisons. Nevertheless, production exposure should not be interpreted as a direct statistical measure of reliability.

Finally, the selected ASDM, ECM, and inverter ECU families should be regarded as representative examples of positive field-performance cases within the available industrial data scope, rather than statistically representative samples of the complete ECU portfolio. The subsequent hardware inspections and validation documentation review were therefore intended to identify recurring engineering characteristics observed among these selected cases. The resulting observations should not be interpreted as universal design requirements or as direct evidence of causal relationships between individual design features and field reliability performance. Instead, they provide engineering insights that may support future reliability-oriented requirement development when considered together with engineering judgement and additional validation activities.

6

Future Work

Several opportunities exist for extending and strengthening the approach in future studies.

6.1 Integration of Detailed Operational Data and Advanced Reliability Modelling

The present study primarily relied on field repair data, engineering databases, warranty information, and production volume records to identify ECU populations with superior field performance. While this approach enabled the development of a practical screening framework, detailed operational and environmental usage data were not available during the study.

Future work could benefit from access to vehicle operating-condition databases containing information such as temperature exposure, humidity conditions, vibration profiles, duty cycles, and vehicle usage patterns. Such data would enable the application of advanced statistical and data-driven methods, including clustering analysis, regression modelling, machine learning techniques, and predictive reliability assessment.

By establishing direct relationships between operating conditions, degradation mechanisms, and field reliability outcomes, a more quantitative methodology for deriving reliability requirements from field performance could be developed.

6.2 Hardware-Level Reliability Screening Through Part Number Traceability

Because direct traceability between exchange numbers and individual hardware part numbers was not fully available within the accessible databases, an alternative way to proceed was found.

Future studies could benefit significantly from establishing a complete mapping between exchange numbers and corresponding hardware part numbers. Such traceability would enable reliability screening at the hardware-variant level rather than at the ECU-family level.

This would allow identification of specific hardware revisions, design generations, or manufacturing variants associated with exceptionally low field repair rates. Consequently, future analyses could provide a more precise understanding of which design implementations contribute most effectively to long-term field reliability.

6.3 Understanding Reliability Mechanisms Through Supplier Collaboration

The methodology developed in this work enables the identification of design features and architectural characteristics associated with successful field performance. However, many underlying design decisions, material selections, manufacturing processes, and qualification strategies remain inaccessible through visual inspection and available engineering documentation alone.

Future work could therefore involve closer collaboration with ECU suppliers and manufacturing organizations in order to obtain additional information regarding PCB materials, stack-up structures, copper thicknesses, surface finishes, solder materials, conformal coating systems, cleanliness requirements, qualification activities, environmental protection measures, and component qualification strategies.

Access to such information would facilitate a deeper understanding of the physical mechanisms underlying the observed field reliability performance. This would support not only the identification of successful design features but also the explanation of why those features contribute to superior long-term reliability in automotive applications.

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