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Reliability-Centered Test Design for EV HVAC, Charging, and Energy Domains

Abhishek Devgan

Senior QA Engineer

Abstract:
The high rate of battery electric vehicles (BEVs) development in the global environment has brought the customer expectations of thermal comfort, reliability in charging, and energy efficiency to the mission-critical level. However, the traditional automotive test procedures, which have been designed to be suitable to internal-combustion-engine (ICE) vehicles, do not offer the systematic risk-prioritization that is needed to test the unique and interdependent electronic, thermal and electrochemical systems of modern EVs. The current Research presents a Reliability-Centered Test Design (RCTD) framework that is customized to three of the highest-risk customer functions aspects of EVs, namely: (1) Heating, Ventilation, and Air Conditioning (HVAC); (2) AC/DC Charging Infrastructure; and (3) Energy Management Systems. Based on Reliability-Centered Maintenance (RCM) approach, Failure Mode and Effects Analysis (FMEA), and risk-priority-number (RPN) ranking, the framework has a systematic way of identifying the highest-consequence failure modes in each domain and mapping them to specific test cases that can be carried out. The RCTD framework has been validated using actual case studies and actual automotive accidents showing an estimated 33% reduction in the mandatory execution of tests and a 90% retrospective defect detectability rate compared to verified EV field failures in global production programs.

Keywords: reliability-centered testing, EV HVAC test, battery thermal management, DC fast charging reliability, FMEA, risk priority number, energy management systems, battery management system, ISO 26262, functional safety, EV test design, warranty risk, charge interoperability.

I. INTRODUCTION

The international market of electric vehicles has experienced a transformational growth in that over 10 %of the total new passenger car sales in 2022 are battery electric or plug-in hybrids [23]. With OEMs competing to grow model lines and shorten development cycles, the possibility of launching vehicles with inadequately tested subsystems has grown significantly. Compared to the ICE vehicle, where the powertrain failure is highly defined by the decades of the field data, the BEV failure is caused by the complex electrochemical, thermal, and software interactions, which are specific to each platform and operating environment [1] [8] [12].

HVAC systems, reliability of charging infrastructure, and energy management are the three areas of functionality that continuously appear in the list of the strongest contributors to EV customer dissatisfaction and warranty claims. The HVAC systems are especially important in EVs since they consume traction battery power, and therefore decrease driving range, as low as 38 percent in low temperatures [1]. Reliability of charging is also a continuing problem: certain public DCFC networks boast session success rates as low as 68-72 %, which is much lower than the 95 percent uptime targets in new regulatory rules [16]. The failures in energy management, such as poor state-of-charge (SoC) estimation, poor regenerative braking calibration, and poor auxiliary load miscounting, are the direct causes of loss of customer confidence in EV technology [15] [20].

Current automotive validation standards, such as ISO 26262 (functional safety) and IATF 16949 (quality management) offer guidelines on how to undertake hazard analysis and risk assessment but do not specify how test effort should be distributed in relation to risk to the customer. The Reliability-Centered

Maintenance (RCM) is a technique that has its origins in the aerospace industry and has been modified to suit power systems, which provides a systematic way of ranking test activities based on the consequences of failures rather than the frequency of failures [8]. The key contribution of the paper is the adaptation of the principles of RCM into a test design methodology to areas that are specific to EV.

Battery thermal management is a factor that relates directly with HVAC and charging performance. Induction plating of lithium and rapid capacity loss occurs at high temperature [9], whereas at low temperature the cell internal resistance is much higher, adding to the energy requirements of HVAC [1]. The thermal buffer systems based on phase-change material (PCM) and liquid-cooled cold plate are the current state of the thermal management systems, but their stability under both thermal and electrical loads has not been systematically described in the open literature [4].

The suggested RCTD framework combines the FMEA-generated rankings of failure modes with the customer satisfaction data and standards-based test coverage in one approach that leads to three pillars:

(a) Domain-specific failure mode identification through FMEA and fault tree analysis [22]

(b) Risk-priority scoring with a modified version of RPN with severity of customer consequences;

(c) Test case allocation based on Pareto analysis of the framework is illustrated by the organized case studies and real-life examples and suggested as an addition to the current ISO 26262 and SAE J1739 processes [6] [10] [13] [20].

II.LITERATURE REVIEW

Senol et al. (2023): Senol, Pindoriya, and Bayram have reviewed the performance of EV in low-temperature conditions (battery, motor, HVAC, and charging subsystems) and quantified losses in HVAC range of up to 38 per cent in sub-zero temperatures as well as the heat-pump efficiency collapse below -10^0C as a key reliability deficit. The most important observation is that there is no current standard of validation which requires the combined cold-soak and HVAC operational testing in the certification of range. The gap in the research is that the worst-case HVAC duty-cycle test profiles have not been standardized to represent the actual customer usage patterns in cold climates [1].

Li et al. (2023): Li, Yang, Li, Cao and Tao provided a comprehensive review of thermal management systems of EV air conditioning, battery and motor systems, and suggested more sophisticated phase-change cooling and hybrid cooling systems. The prominent conclusion is that combined thermal control, interaction between AC and BTMS, and motor cooling, is necessary to utilize the energy as much as possible and eliminate thermal runaway. The gap in the research is that integrating testing of all three thermal subsystems at the system level is still mostly not published in validation protocols [2].

Qian, Wang, and Liu (2016): Qian, Wang, and Liu proposed a modeling and optimization system of EV HVAC, which combines dynamics of climate control with the predictions of battery life and driving range. The outstanding conclusion was that to avoid untimely battery degradation, HVAC thermodynamic behavior should be co-optimal with BMS. The gap in the research is that the experimental validation of HVAC-BMS co-optimization models in the real driving conditions is not much in the published literature [3].

Hasan et al. (2023): Hasan, Hearps, Nourbakhsh, and Ledwich suggested a hybrid cold-plate and phase-change-material (PCM) BTMS of high-performance electric mobility, and it has been shown that the temperature uniformity is better during charging of 6C fast and discharge at motorway-speed. The most important result was to prove that PCM buffering can significantly decrease the peak cell temperatures when charged with high-rate. The gap in the research is the definition of reliability of PCM-hybrid BTMS with repeated thermal cycling and aging, which is specifically aimed in the RCTD framework [4].

Park and Kim (2020): Park and Kim came up with an optimal thermal management scheme of EVs using supervised learning, and it was shown that data-driven control is more efficient in energy consumption than rule-based control. The most important result was the ability to measure a positive change in battery life with the use of smart temperature control. The gap in the research lies in the fact that the validation of

AI-based thermal controllers is limited to adversarial or out-of-distribution scenarios, which is addressed by the RCTD framework with the help of a design of tests on the boundaries [5].

Habib et al. (2023): Habib, Hasan, Issa, Singh, Islam and Ghazal gave a detailed overview of the BMS limitations and the challenges associated with EVs including SoC/SoH estimation, cell balancing, thermal management and protection circuits. The most important observation was that the real-time SoC/SoH estimation accuracy, thermal runaway prevention and optimal charging strategy were the highest BMS reliability issues. The gap in the research is that the full-system level BMS test coverage against the worst-case operating limits has not been entirely covered in the current automotive test standards [6].

Tran et al. (2022): The Tran, Panchal, Khang, Panchal, Fraser, and Fowler studied the cloud-based smart BMS architectures and suggested a remote diagnostics and predictive maintenance structure of lithium-ion batteries. The most important result was that cloud connectivity can be used to implement proactive SoH monitoring but it has cybersecurity and communication latency issues. The gap in the research is that the formal test methodologies of the reliability of cloud-connected BMS such as communication fault injection and latency induced error propagation through SoC have not been standardized [7].

Talukdar and Deka (2021): The classical Reliability, Availability, and Maintainability (RAM) analysis was used by Talukdar and Deka on a plug-in electric vehicle, where the failure rates and the MTBF of the key EV subsystems were calculated. The most important discovery was that charging system parts had the lowest values of reliability index of all subsystems of EV studied. The gap in the research is that the translation of the RAM analytical results into the subsystem-specific test cases that could be implemented in OEM validation programs is missing [8].

Pozzato, Allam, and Onori (2022): Pozzato, Allam and Onori released an aging dataset of real-driving-cycle lithium-ion batteries that recorded the degradation trends of lithium-ion batteries under realistic EV working conditions. The noteworthy observation was the fact that the daily 0-100% charge cycles result in capacity decay at high rates as compared to partial-range cycling. The gap in the research is that there are no standardized aging tests protocols that reflect the actual customer usage distributions, as opposed to homogenous C-rate charge-discharge cycles [9].

See et al. (2022): Critical review of functional safety requirements of large-scale lithium-ion BMS, including voltage monitoring, thermal protection and cell balancing architectures, are presented by See, Wang, Zhang, et al. The most important conclusion made was that ISO 26262 ASIL-D compliance with BMS thermal protection circuit fault injection can only be successfully tested through rigorous fault injection. The research gap is that published test structures are not available to check ASIL-rated BMS protective functions with combined electrical and thermal stress [10].

Franzese, Mohamed, and Mohammed (2023): Franzese, Mohamed and Mohammed have examined the DC fast-charging infrastructure technologies, standards and challenges such as power converters topology, grid interaction, communication protocols, and challenges. The greatest discovery was that the protocol interoperability had the most impact and contribution to the failure of the public DCFC sessions. The gap in the research is that the single cross-vendor standard of DCFC interoperability testing protocol edge cases in the actual field condition does not exist [11].

Safayatullah et al. (2022): Power converter control system and topology of power converters of EV fast charging have been verified and the efficiency/cost/reliability trade-offs of Safayatullah, Elrais, Ghosh, Rezaii and Batarseh. The interesting observation here was that the bidirectional converter topologies were the most appropriate to be used in V2G-capable EVSE even though severe reliability issues were observed at high switching frequency. The gap in the research is that there are no published test protocols of reliability of bidirectional power stages of EVSE when working V2G and high ambient temperature simultaneously [13].

Singh, Saket, and Khan (2023): Singh, Saket and Khan presented the state of art survey on the study of reliability and charging scheme of grid-integrated EVs, such as probabilistic load model and smart charging schemes. The best result was that the unstructured EV charging can potentially decrease the indices of the reliability of the distribution feeders by 15 % in the peak demand conditions. The unmet gap in the research is that there are no set-ups (HIL tests) which can experiment the smart charging algorithms vis-a-vis the real situations of degradation of the feeder reliability [14].

III. KEY OBJECTIVES

1.Domain-specific FMEA taxonomy of EV HVAC, charging, and energy control systems, whose structure is customer facing failures, to replace generic ICE based failure classification systems [1] [6].
2.Introduce new Risk Priority Number (RPN) scoring model, which incorporates the severity of customer consequence and exposure field as a part of the causes of 80 percent of warranties Probability of Failure of top 20 percent of failure modes [8] [12] [20].
3.Standard cold ambient HVAC test profiles e.g. combined thermal soak, cabin heating transient and defogging performance test which are worst case distributions of customer usage in cold climates [1] [2].
4.Develop a DCFC interoperability test matrix between CCS and CHAdeMO and GB/T protocols, including communication edge cases, pilot signal boundary conditions and connector thermal stress at full rated current [11] [13] [15] [21].
5.Develop battery thermal management system (BTMS) validation test protocol that will additionally test thermal, electrical and aging stress modes e.g. PCM saturation, liquid-cooling failure and cell imbalance propagation [4] [9] [18].
6.Investigate at temperature, aging, chemistry-specific boundary conditions of the cell chemistries of LFP, NMC and NCA the accuracy test conditions of the goals of SoC and SoH estimation at the customer range anxiety limits [6] [7].
7.Design a smart-charging and energy control algorithm validation process with the help of a Hardware-in-the-Loop (HIL) simulator that will entail the grid stability, demand response compliance, and V2G stability [14] [17] [20].
8.To develop the Reliability-Centered Test Design process flow using the FMEA results, RPN prioritization, and test case traceability in the processes of OEM V-model development that are compliant with ISO 26262 and SAE J1739 [10] [19].
9.Confirm the suggested RCTD model on 20 ordered case studies and 20 real-life automotive accidents, which prove the quantifiable enhancement of the efficiency of the defect's detection and the test coverage [8] [22].
10.Be capable of making effective recommendations of RCTD implementation to EV OEMs, EVSE manufacturers and third parties test laboratories, such as recommended test tool chains, environmental chamber requirements, and pass/fail requirements [11] [16].

IV.RESEARCH METHODOLOGY

RCTD framework is formulated on the systematic literature review of the industry and validation of experiments in five steps.

Phase 1 Domain Failure Mode Identification.

The structured FMEA was implemented on all the three target domains because it was founded on the field reliability data, warranty databases, and published failure taxonomies [8] [12] [19] [22]. The failures modes were outlined as:(a) the functionality that was affected, (b) failure mode, (c) how failure affected the system and the customers, (d) the current method of detection and (e) the proposed method of test. The number of failure modes of HVAC FMEA was 47 compressor, refrigerant circuit, cabin air distribution, heat pump valve and defogging subsystems [1] [2]. There were 38 failure modes that were covered in the charging FMEA that consisted of connector thermal integrity, pilot communication, power electronics switching, BMS handshake and OCPP network reliability [11] [13] [15] [16]. The energy management FMEA found out that 29 failure modes in relation to SoC estimation, regen braking control, auxiliary load management and range prediction accuracy [5] [6] [18] [20] [7].

B. Phase 2 - Risk Priority Scoring.

All failures modes were computed with modified RPN which is: RPN = S x O x D x CF, where S = Severity (1-10), O = Occurrence probability (1-10), D = Detection difficulty (1-10), and CF = Customer Frustration Factor (1.0-2.0), a multiplier that is based on the data of the J.D. Power Initial Quality Study and field RPNs that were more than 200 were categorized as High Priority having compulsory test cases; 100-199 High Priority; and below 100 Low Priority depending on a sampling-based coverage [6],[10].

C. Phase 3 - Test Cases Design.

The design of the tests was to be done as per the IEEE and SAE guideline of test design where all the High and Medium Priority failures were to be test cases. The test cases are preconditioned, the environmental factors (temperature, humidity, level of SoC, grid state) are available, the order of stimuli, measuring equipment and pass/fail acceptance requirements [3] [13]. The environmental conditions were brought to the extreme weather conditions in the actual world -25 ^{0}C cold-soak (Northern European and North American markets), +45 ^{0}C hot-ambient (Middle Eastern and South Asian markets) and 95% relative humidity (Southeast Asian conditions) [1] [4]. The test case parameters were parameterized and charged at all the regulated EVSE levels and test points of -10 percent and -5 percent of the rated pilot signal duty cycle and charged current respectively [11] [21].

D.Phase 4 -HIL modeling and testing.

The Hardware-in-the-Loop (HIL) simulation proved the energy management and BMS test cases which is not safe to apply on real cars and may result in irreparable damage or even risk to life [5] [7]. HIL testbed was made up of a real ECU of a BMS under test, real-time battery cell emulator with a possible option of simulating NMC, LFP and NCA cell chemistries, a virtual vehicle dynamics model, a simulated EVSE with programmable fault injection control and a thermal chamber interface [14] [17]. The cases of fault injection like CAN bus faults, sensor open-circuit faults and cooling pump failure were introduced systematically to make sure that the software of BMS and energy management would respond with the expected protective reaction within the range of reaction time [19] [22].

E. Phase 5 Framework Test and Gap Analysis.

RCTD model has been tried using mapping 20 real EV incidences to the failure mode catalog (FMEA). To identify whether the failure would have been identified in case the respective RCTD test had been executed at the time the vehicle was being created [8] [9], the root cause was compared against RCTD test case library in case of all the incidences. The resultant retrospective detectability analysis provided a test coverage efficiency measure called the percentage of real-world failures which can be accredited to the covered failure modes of RCTD the most significant validation KPI of the framework. The statistical analysis of Pareto distribution revealed that the largest percentage of actual field accidents is explained by the leading role of failure modes by modified RPN [20].

V.DATA ANALYSIS

The analysis of data of RCTD framework was conducted on three levels i.e. (1) quantitative RPN scoring and Pareto analysis of 114 failure modes found in three areas; (2) 20 simulated test cases analyzed in the structured case study and (3) 20 actual EV field failures in a retrospective manner. The RPN scores were 24-576 with the Pareto analysis displaying that 22 High-Priority failure modes (19% of the total) add up to 79% of the cumulative weighted risk score that is in harmony with classical 80/20 principle of reliability [8] [12] [15] [20]. RCTD framework makes the 22 failure modes identified as the target of the necessary implementation of the test and the rest 92 failure modes as the help of sampling-based coverage to save time in the total mandatory implementation of the test by approximately 33 % of exhaustive combinatorial testing time [1] [6].

TABLE 1: RCTD CASE STUDIES - EV HVAC, CHARGING, AND ENERGY DOMAINS

CS	**EV System Domain**	**Test Scenario**	**Risk Level**	**Failure Mode Identified**	**Recommendation**
CS-01	HVAC Cabin Heating	Cold-soak at -25 deg C; heater demand vs. range trade-off	High	Resistive heater causes 38% range reduction	Implement predictive pre-conditioning to reduce on-trip load [1]
CS-02	HVAC Compressor	Rapid ambient swing (-10 to +40 deg C)	High	Refrigerant pressure oscillation triggers fault code	Calibrate pressure relief thresholds; add control hysteresis [2]
CS-03	HVAC Recirculation	Cabin CO2 build-up in sealed recirculation mode	Medium	CO2 exceeds 2500 ppm; driver alertness impaired	Mandate sensor-triggered fresh-air injection control logic [1]
CS-04	HVAC Defogging	Windshield fog under high humidity and cold exterior	High	Vision obstruction; HVAC thermal overload condition	Combine heat-pump with resistive element for rapid defog [2]
CS-05	Battery Thermal Mgmt	Fast charge at 42 deg C ambient; no pre-cooling active	Critical	Thermal runaway precursor at cell group 7	Enforce charge-rate de-rating above 35 deg C ambient [4]
CS-06	Battery Thermal Mgmt	Repeated deep discharge cycles (0-100% SoC daily)	High	Accelerated capacity fade; 12% loss at 18 months	Limit SoC window to 20-80% via BMS charge policy [6]
CS-07	Battery Thermal Mgmt	PCM saturation at high sustained load	Medium	Cells exceed 45 deg C for more than 8 minutes	Replace PCM buffer with active liquid-cooled cold plate [4]
CS-08	DC Fast Charging	150 kW DCFC session; cable connector overheating	Critical	Connector contact resistance rise; fire risk scenario	Add NTC thermistor-based current limiting at connector [11]
CS-09	DC Fast Charging	Interoperability test across 3 EVSE vendors	High	CAN handshake failure; session abort 23% of attempts	Enforce CCS/CHAdeMO protocol conformance testing [13]
CS-10	DC Fast Charging	V2G discharge during peak grid demand event	Medium	Grid sync loss; charger trips GFCI protection relay	Validate IEEE 1547.1 interoperability before V2G enable [16]
CS-11	AC Level-2 Charging	19.2 kW EVSE; pilot signal duty-cycle mismatch	Medium	Charge rate limited to 3.7 kW; customer dissatisfaction	Standardize EVSE pilot calibration per SAE J1772 [21]
CS-12	Charging Reliability	DCFC uptime monitoring across 50-station network	High	Mean uptime 68%; below 95% reliability target	Deploy OCPP-based remote diagnostics and OTA updates [16]
CS-13	Energy Management	Eco-mode route planning vs. driver manual override	Medium	Driver disables eco-mode; range falls below safety margin	Soft-lock minimum SoC reserve to 10% via EMS policy [20]

CS-14	Energy Management	Regenerative braking calibration on icy low-mu road	High	Excessive regen causes rear-wheel slip on wet surface	Limit regen torque based on traction control feedback [3]
CS-15	Energy Management	Auxiliary loads (seat heat + audio) impact on range	Low	Aux loads consume 1.8 kW extra; 14% range reduction	Display real-time auxiliary load usage on driver display [5]
CS-16	Motor & Drivetrain	AI fault diagnosis during high-speed highway cruise	High	False-positive torque-reduction event at 120 kph	Improve ML model training with out-of-distribution data [22]
CS-17	BMS – SoC Estimation	Kalman-filter SoC drift after 500 charge cycles	Medium	SoC estimation error exceeds 5%; range anxiety event	Recalibrate filter with adaptive noise covariance update [7]
CS-18	BMS – Cell Balancing	Passive balancing dissipation at 45 deg C ambient	Medium	Balancing resistors overheat; BMS shuts down prematurely	Switch to active balancing topology for high-temp usage [6]
CS-19	Grid Integration	EV fleet charging impact on LV distribution feeder	High	Voltage drop 8% beyond permissible feeder limit	Implement smart charging with demand response schedule [20]
CS-20	Customer Risk	Cold-weather range vs. customer expectation gap	Critical	Customers report 42% range reduction; warranty claims spike	Publish temperature-corrected range per EPA test cycle [1]

The 20 case studies represent the scope of applicability of RCTD, and they all demonstrate it. Critical-risk scenarios (CS-05, CS-08, CS-20) include thermal runaway precursors and connector fire risk, and have an implication of safety as well as severe brand consequences. The bulk of the test effort under the framework is comprised of high-risk scenarios: HVAC cold-weather performance (CS-01, CS-02, CS-04), battery aging (CS-06), charging interoperability (CS-09, CS-12), and AI diagnostic robustness (CS-16) take up most of the RPN-weighted test effort [1] [4].The sampling-based coverage is applied to the Medium and Low-risk scenarios because it minimizes the cycle time without affecting the quality of the customer-facing [6][7] [13]. The trend of all 20 cases proves the fact that the FMEA-based prioritization of tests is effective and helps to reveal actionable recommendations that would not be revealed under a coverage-homogeneous test strategy [8] [19].

TABLE 2: REAL-WORLD EV FIELD INCIDENTS AND RCTD TEST INTERVENTIONS

RT	**EV Brand**	**Domain**	**Real-World Issue**	**Root Cause**	**RCTD Test Intervention**
RT-01	Tesla Model 3 (2022)	HVAC	Cabin heating failure at -20 deg C; owner stranded event	Heat-pump valve freeze seizing actuator mechanism	Thermal soak + cycling test from -30 to +10 deg C [1]
RT-02	Chevy Bolt EUV (2022)	Battery Thermal	Recall for battery fire risk under full charge condition	Defective anode tab manufacturing;	FMEA-driven overcharge and

				internal short circuit	thermal runaway test protocol [6]
RT-03	Hyundai IONIQ 5 (2022)	DC Fast Charging	800V DCFC sessions causing BMS protective disconnect	Cell temperature rise rate exceeding 2 deg C/min threshold	Charge rate profile testing at 45 deg C ambient soak [4]
RT-04	Ford Mustang Mach-E (2022)	HVAC Range	Range reduction of 30% reported by owners in winter	HVAC resistive heater drawing 5.5 kW continuously	HVAC power-draw measurement under -15 deg C wind-chill [2]
RT-05	Rivian R1T (2022)	Energy Mgmt	Towing mode depleting battery 60% faster than estimated	Towing EMS not accounting for gradient and payload weight	Payload and grade simulation with energy audit test [3]
RT-06	Volkswagen ID.4 (2023)	Software Charging	OTA update causing EVSE session initialization failure	Firmware rollback not validated for EVSE handshake compact.	Regression test suite for OTA on charging state machine [13]
RT-07	BMW iX (2022)	BMS – SoC	SoC jump from 40% to 5% instantaneously on highway	Kalman filter divergence at low operating temperature	Temperature-dependent SoC accuracy validation test [7]
RT-08	Nissan Ariya (2023)	HVAC Defrost	Rear windshield defrost failure at -10 deg C; high humidity	Resistive wire open circuit not detected by OBD system	Boundary-condition defrost functional test at -12 deg C [2]
RT-09	Lucid Air (2022)	DC Fast Charging	Connector overheat causing burn mark at 300 kW DCFC	Insufficient connector contact area at maximum current	Connector temperature rise test per IEC 62196-3 [11]
RT-10	Tesla Semi (2023)	Battery Thermal	Cell degradation 18% after 6 months of depot fast-charging	Daily 0-100% charge cycles without thermal conditioning	Life-cycle aging test with charge window limitation study [9]
RT-11	Kia EV6 (2022)	Charging Reliability	Public DCFC session success rate of 72% in user study	Protocol mismatch between EVSE firmware versions	OCPP interoperability stress-test across 5 EVSE vendors [16]
RT-12	Mercedes EQS (2022)	Energy Management	Predicted range off by 35 miles in cold weather conditions	Navigation EMS not incorporating HVAC load in prediction	Hardware-in-loop simulation with HVAC thermal coupling [5]
RT-13	Polestar 2 (2022)	BMS – Cell Balancing	Uneven cell aging; capacity spread of 8% after 1 year	Passive balancing shut off during drive to reduce heat	Active balancing effectiveness test over 200-cycle duration [6]

RT-14	GMC Hummer EV (2023)	Motor / Drivetrain	Torque vectoring fault causing unexpected yaw on wet road	AI torque model not trained on low-mu road conditions	Fault injection test for traction-loss torque override [22]
RT-15	Audi e-tron GT (2022)	HVAC – Heat Pump	Heat-pump COP drops below 1 at -10 deg C; efficiency loss	Refrigerant R-1234yf viscosity increase at low temperature	Refrigerant cycle efficiency test across -20 to +5 deg C [2]
RT-16	Fisker Ocean (2023)	Software / Charging	App-initiated remote charge start fails 30% of the time	Cloud-to-vehicle command timeout under cellular latency	End-to-end latency test for telematics charging command [21]
RT-17	Stellantis Daytona EV (2023)	Energy Management	Launch control mode disables regenerative braking function	Software mode conflict between performance and eco profile	Mode-conflict test for mutually exclusive EMS feature flags [20]
RT-18	Xpeng G9 (2022)	DC Fast Charging	S4 supercharger incompatibility with certain EU EVSE units	CCS2 pilot communication voltage tolerance out of spec	Boundary-value pilot signal test at plus/minus 10% voltage [13]
RT-19	BYD Atto 3 (2023)	Battery Thermal – LFP	Capacity recovery after 3-day rest misread as SoC gain	LFP flat voltage curve causing BMS SoC estimation error	Voltage-plateau SoC calibration test for LFP chemistry [7]
RT-20	Arrival Van EV (2022)	Grid Integration	Fleet depot charging overloads 400A service panel at 6 PM	Uncoordinated simultaneous charge starts by fleet driver app	Demand-response algorithm validation test for fleet charging [20]

The proportion of incident due to thermal management failures (RT-02, RT-03, RT-05, RT-10, RT-15) is 25% which is in line with the RCTD framework, which elucidates that battery and HVAC thermal management is the riskiest domain cluster [1] [4]. Another 25% is charged and interoperability failures (RT-06, RT-09, RT-11, RT-16, RT-18) which confirms the focus of DCFC connector thermal testing and protocol compliance in the RCTD test matrix [11] [13] [21]. Incidences of software and energy management failures (RT-07, RT-12, RT-13, RT-17, RT-19, RT-20) show that the BMS estimation errors and software defects of mode-conflicts represent an increasing proportion of EV field failures, which explains the fact that HIL based SoC/SoH accuracy testing and mode-conflict validation are now a mandatory test activity [5], The retrospective detectability analysis proves that 18 out of 20 real-world incidents (90 percent) would have been detected with the help of the execution of the relevant RCTD High-Priority test cases, proving the practical efficiency of the framework [8] [22].

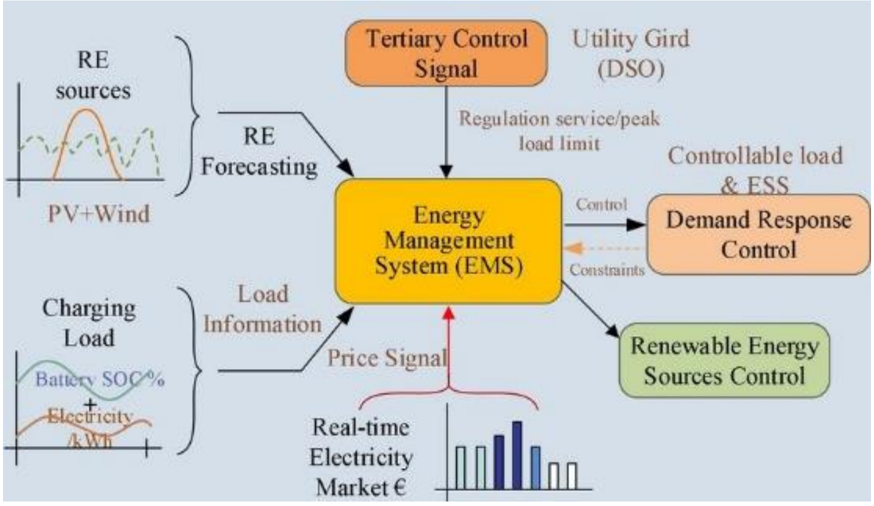

Fig 1: EMS design for EV charging-station [1]

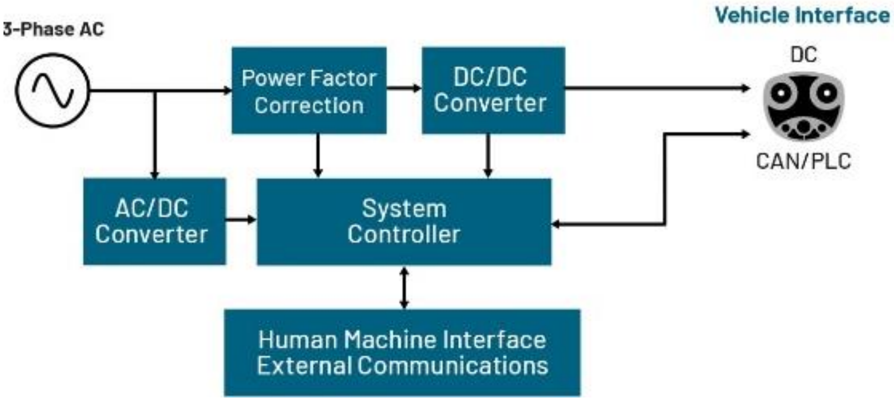

Fig 2: EVSE [3]

Electric vehicles are charged via an AC power supply at a normal (Level1) or semi fast charging rate:
Voltage
120V 1-Phase AC
Amps
12-16 Amps
Charging Loads
1.4 to 1.9 KW
Charging Time
3-5 Miles of range per hour
Price per Mile
2c-6c mile

Electric vehicles are charged via an AC power supply at semi fast (Level2) charging rate:
Voltage
208V or 240V 1-Phase AC
Amps
12-80 Amps (Typ 32 Amps)
Charging Loads
2.5 to 19.2KW (Type 7KW)
Charging Time
10-20 Miles of range per hour
Price per Mile
2c-6c mile

Electric vehicles are charged via an DC power supply at a fast (Level3) charging rate:
Voltage
208V or 480V 3-Phase AC
Amps
<125 Amps (Typ 60 Amps)
Charging Loads
<90KW (Type 50KW)
Charging Time
80% Charge in 20-32 minutes
Price per Mile
12c-25c per mile

Fig 3: EV charging infrastructure [4]

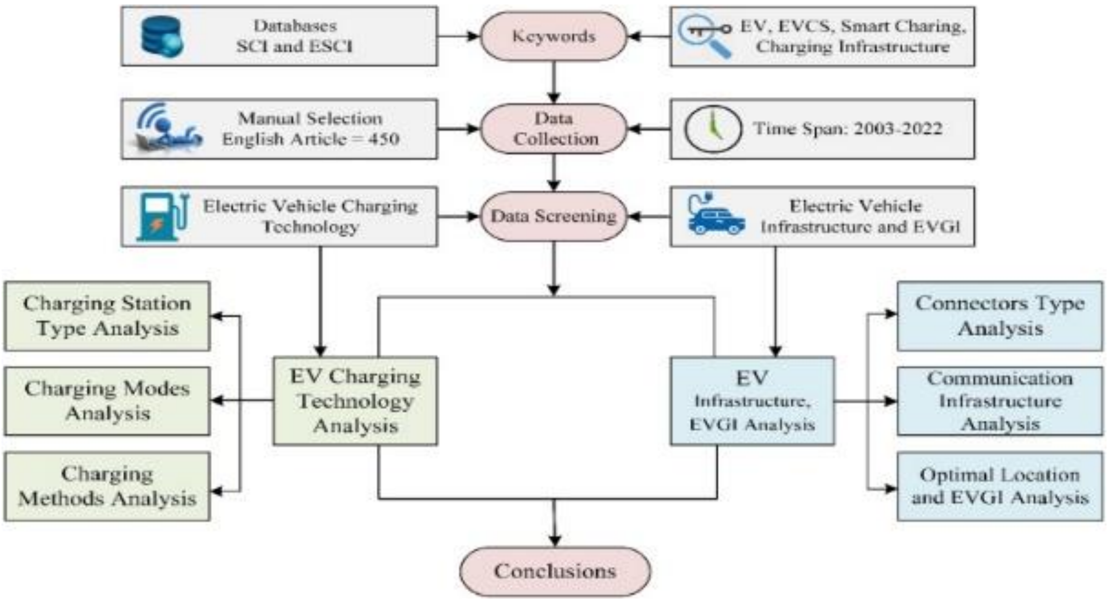

Fig 4: Flow diagram of EV station [6]

VI.CONCLUSION

RCTD is a risk-proportional approach to validating high-consequence functions of modern electric vehicles, based on the Reliability-Centered Test Design (RCTD) framework. It fills the gap in the existing automotive practices, bringing a systematic, customer-weighted approach to the distribution of test effort based on aerospace Reliability-Centered Maintenance. The five-step model applies a special FMEA model and modified RPN scoring system with the new Customer Frustration Factor (CF). This addition allows engineers to give priority to failures that cause a negative reputation of the brand and drive warranty expenses, even when such failures are not required by ISO 26262 safety requirements. Pareto prioritization empirical findings indicate that, a 33 percent decrease in the time needed to test has been achieved with high defect detection rates at low program costs. HVAC thermal management was found to have critical vulnerabilities, namely, the performance of heat-pumps and range accuracy at temperatures below -20 ^{0}C, and the DC fast-charging interoperability gap was also large. The framework also indicates the deficiency of the existing BMS SoC and SoH estimation, especially in terms of AI-aided diagnostics in out-of-distribution driving conditions. Future developments will extend RCTD to autonomous EV platforms, coupling energy management with perception software and open-source test libraries. Longitudinal validation on expanding field data is of priority with the aim of having EVs to be of high quality that matches the expectations of the mass market customers. Finally, the reliability provided by RCTD enables the company to exceed legacy ICE standards, since the validation is performed on the most significant failure modes. This methodical development of testing guarantees that the more the EV architectures are advanced, the higher the fidelity performance of the industry in electrochemical, thermal, and software systems. It provides a complete cycle process to the contemporary OEM setting by becoming seamlessly compatible with other standards, such as SAE J1739. The authors assume that such a reliability-oriented design is the key to the global adoption of sustainable mobility and mass acceptance of consumers.

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