Centre of Excellence for Zero Emission Trucking

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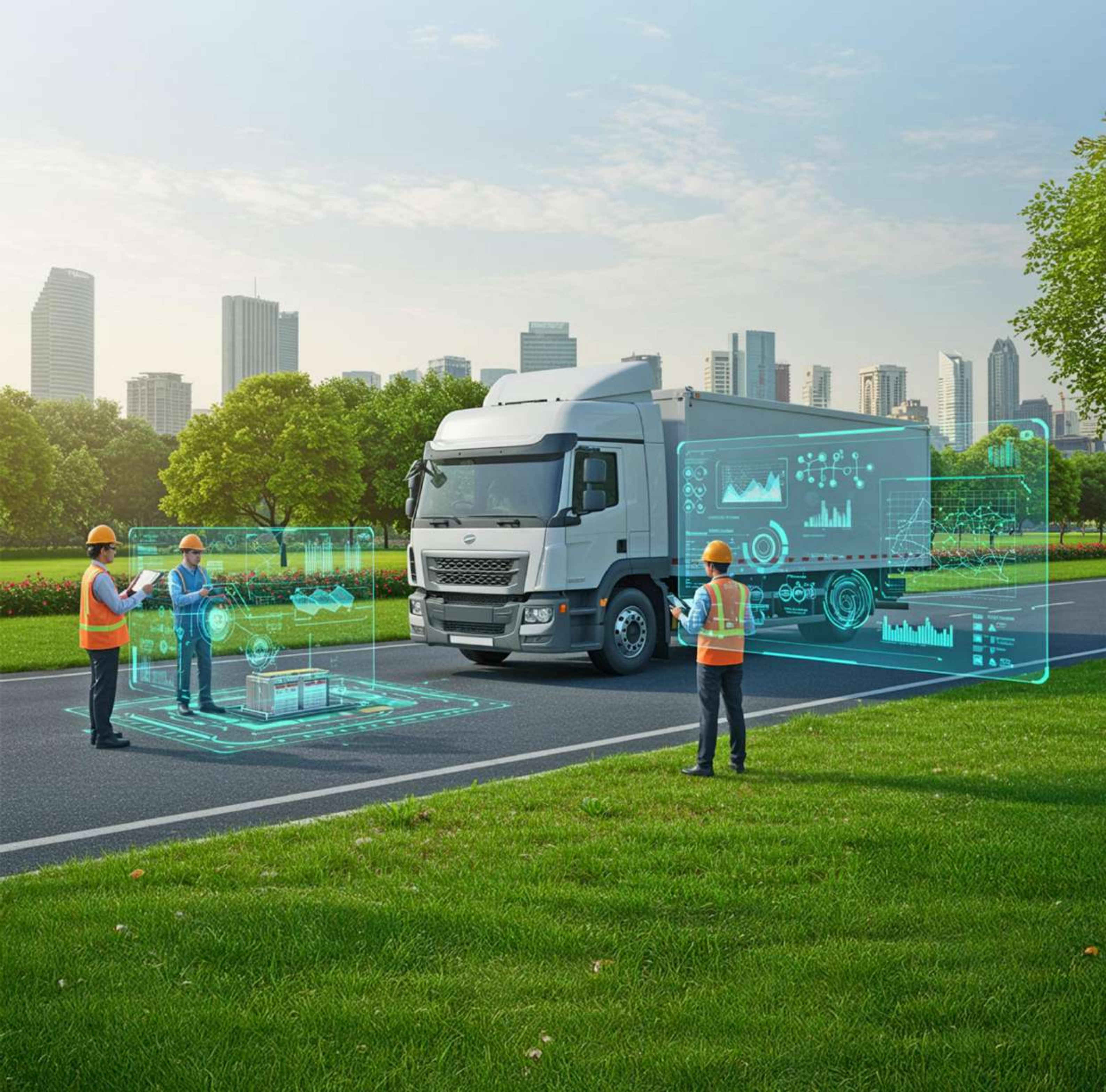
FAILURE MODES AND EFFECTS ANALYSIS (FMEA) FOR BATTERY ELECTRIC TRUCKS



Preface

Dear All,

We are pleased to share with you our latest report, "Failure Modes and Effects Analysis (FMEA) for Battery Electric Trucks (BETs)," prepared by the Centre of Excellence for Zero Emission Trucking (CoEZET), IIT Madras, in association with RLE India & RLE FutureMotiv, UK. This study provides a structured risk assessment methodology to enhance the reliability and safety of Battery Electric Trucks in the Indian operating environment.

The report presents a Design Failure Modes and Effects Analysis (DFMEA) covering five major subsystems: Electrical System (Body Control System - BCS), Chassis System (Axle & Suspension), Propulsion System, High-Voltage Energy Management System (HVEMS), and Interior Systems (IP Dashboard & Controls). Utilizing the AIAG-VDA methodology, this analysis systematically identifies potential failure modes, assesses their risks, and recommends mitigation strategies to improve vehicle performance.

Given India's diverse and extreme operating conditions, the study considers high-temperature environments (up to 52°C), extreme cold conditions (-20°C to -40°C), flooding scenarios with water wading depths of up to 500mm, and overloading conditions with vehicles operating at 25% to 50% above their Rated Gross Vehicle Weight (GVW). The findings provide valuable insights into high-risk failure modes and propose design improvements to align BET development with ISO 26262 and other industry standards.

We believe this report will be a valuable resource for OEMs, policymakers, researchers, automotive engineers, and other industry stakeholders working towards the adoption and advancement of Zero Emission Trucking (ZET). We invite you to review this document and leverage its insights to enhance the design and deployment of robust, high-performance BETs.

This FMEA report is generic in nature which is common to all battery electric trucks working in Indian extreme operating conditions and is not specific to any particular model of BET. This report provides an overall risk assessment methodology applicable to Battery Electric Trucks. This report addresses all the failure modes at system level, subsystem/aggregate level and do not cover component level failures. OEMs and other users can take the inputs from this FMEA report and can customize their DFMEA analysis based on the actual components, systems, and configurations fitted in their specific model of trucks.

Please do not hesitate to reach out if you require any further information or discussion on the findings of this report. We look forward to your valuable feedback in fostering a sustainable future for electric mobility.

Best regards,

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Disclaimer

This FMEA report is generic in nature which is common to all battery electric trucks working in India under extreme operating conditions and is not specific to any particular model of BET. This report provides an overall risk assessment methodology applicable to Battery Electric Trucks. This report addresses all the failure modes at system level, subsystem/ aggregate level and do not cover component level failures. OEMs and other users adopting this FMEA may need to customize their DFMEA analysis based on the actual components, systems, and configurations fitted in their specific models of trucks. The findings and recommendations in this document should be reviewed in the context of the real-world design and operational conditions of the vehicles.

Abstract

This report presents the Design Failure Modes and Effects Analysis (DFMEA) conducted for the key systems of Battery Electric Trucks (BETs) to assess potential risks and improve system reliability. The analysis covers five major subsystems: Electrical System (Body Control Module), Chassis System (Axle System), Propulsion System (E-Axle System), High-Voltage Energy Management System (HVEMS), and Electrical System – Instrument Cluster. The FMEA follows the structured AIAG-VDA methodology given in FMEA Handbook (Fist Edition 2019) published by Automotive Industry Action Group and VDA (Verband der Automobilindustrie), ensuring a systematic approach to identifying failure modes, their causes, and recommended mitigation strategies.

The study considers extreme operating conditions specific to India, including high temperatures up to 52°C, extreme cold temperatures (-20°C to -40°C), and flooding scenarios with water wading depths ranging from 200mm to 500mm at various speeds. It also evaluates truck performance under overloading conditions, with vehicles operating at 25% to 50% above their Rated Gross Vehicle Weight (GVW). Additionally, the assessment includes varied road conditions, such as highways, expressways, semi-paved roads, salt pan terrains, river sand environments, and mining applications for tipper trucks.

The findings from this report highlight key high-risk failure modes, their Action Priority (AP) scores, and proposed design improvements to enhance vehicle safety and performance. This DFMEA serves as a critical risk assessment tool, aiding in the development of a robust and reliable BET design that aligns with ISO 26262 and other industry standards.

Table of Contents

Contents

Abbreviations

Short Term	Description
AP	Action Priority
AC/DC	Alternating Current/ Direct Current
BCM	Body Control Module
BCS	Body Control System
BET	Battery Electric Truck
BTMS	Battery Thermal Management System
CAN	Controller Area Network
CoEZET	Centre of Excellence for Zero Emission Trucking
D	Detection
ECC	Error Correction Code
EDS	Electrical Distribution Systems
ENV	Environment
FMEA	Failure Modes and Effects Analysis
H	High
HMI	Human Machine Interface
HV	High Voltage
HVEMS	High Volage Energy Management System
GVW	Gross Vehicle Weight
ICE	Internal Combustion Engine
IGBT	Insulated-Gate Bipolar Transistor
L	Low
LIN	Local Interconnect Network
LV	Low Voltage
M	Medium
O	Occurrence
OEM	Original Equipment Manufacturer
RFQ	Request for Quotation
S	Severity
SEU	Single Event Upset
TID	Total Ionizing Dose
VCU	Vehicle Control Unit

List of Figures

List of Tables

1. Introduction

This report presents the Failure Modes and Effects Analysis (FMEA) conducted for the Battery Electric trucks. The purpose of this analysis is to identify potential failure modes, assess their impact, and determine corrective actions to mitigate risks. This study is conducted by RLE India/RLE FutureMotiv (FM), with engineering locations in the United Kingdom and India and in association with Centre of Excellence for Zero Emission Trucking (CoEZET) of IIT Madras.

This FMEA is expected to benefit the Zero Emission Trucking (ZET) community by providing a structured methodology to assess and mitigate risks associated with battery electric trucks. The insights gained from this analysis can be utilized by researchers, policymakers, and automotive engineers working on the development and deployment of Battery Electric Trucks. Additionally, industry stakeholders, including OEMs, suppliers, and regulatory bodies, can leverage this report to enhance vehicle reliability and safety.

2. Requirements

The FMEA for Battery Electric Trucks (BETs) has been developed considering the following unique and extreme Indian operating conditions, as specified by CoEZET, IIT Madras. These conditions impact vehicle performance, reliability, and safety.

1. Extreme High Temperatures (Up to 52°C)

- Trucks operating on roads under direct sunlight and extreme heat.
- Vehicles parked on roads exposed to hazards such as molten tar, high winds, and radiation.

2. Flooding and Water Wading Conditions

- Trucks wading through water depths of 500mm, 400mm, 300mm, and 200mm.
- Water wading distance: 1 km at speeds of 20, 25, 30, 35, and 40 km/h.
- Consideration of water splashing, tire traction, and torque requirements in wet and slippery conditions.

3. Extreme Cold Temperatures

- Condition 3a (-20°C): Commonly experienced in Himalayan regions of northern India during winter.
- Condition 3b (-40°C): Some regions experience extreme freezing conditions, affecting battery performance, electrical components, and vehicle subsystems.

4. Truck Loading Conditions

- Vehicles operating at Rated Gross Vehicle Weight (GVW) as per the matrix given by CoEZET, IIT Madras.
- Following two overloading scenarios were considered:
    - Overload up to 25% of GVW
    - Overload up to 50% of GVW

5. Road Conditions

The following road types are considered for FMEA analysis:

- Highways & Expressways (paved, high-speed driving).
- State Roads connecting highways and expressways.
- Dusty Semi-Paved Roads (rough gravel with potholes and ruts).
- River Sand & Salt Pan Roads (abrasive and corrosive environments).
- Mining Tracks (extreme load conditions affecting suspension and chassis).

6. Vehicle Matrix

Following vehicle matrix was considered in this DFMEA report.

Sl. No.	Axle	Rated GVW (kg)	Vehicle Category
1	4x2	13000	Haulage
2	4x2	18500	Haulage
3	6x2/6x4	30000	Tipper
4	8x2/8x4(Tri-Axle)	37000	Haulage
5	10x2/10x4 DTLA	48000	Haulage
6	6x2/6x4	55000	Tractor Trailer

7. Vehicle Topology

Following vehicle topology was considered for this FMEA report.

- Vehicle with Centre Motor and Propeller shaft connecting rear-wheel drive.
- E-Axle (4x2, 6x2 and 6x4 (Tandem E-Axle)).
- Lithium-ion Battery pack mounted at the belly area.
- No Hub Motor option.

3. Project Scope

Figure 1 represents a structured framework for analysing potential failure modes in a Battery Electric Truck (BET) through DFMEA (Design Failure Modes and Effects Analysis). It provides a visual representation of different influencing factors that contribute to failure risks in vehicle areas such as Propulsion, HVEMS, Chassis (Axles), Instrument Cluster, and Body Control Module.

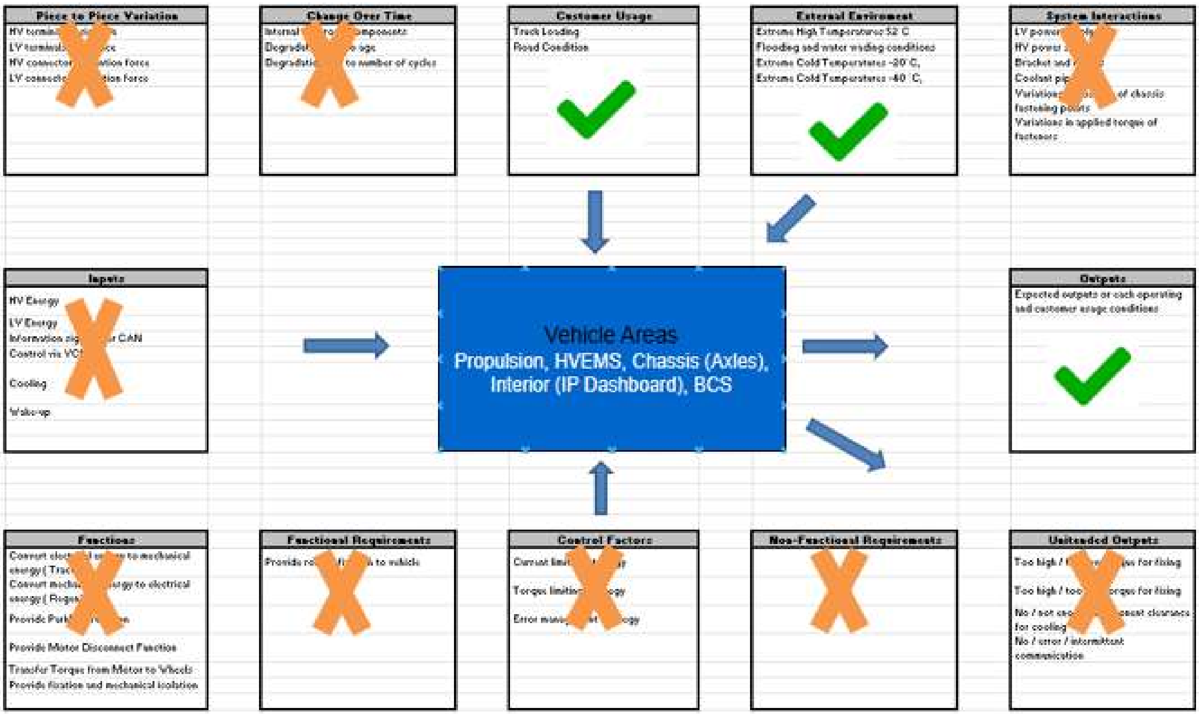

Figure 1: Snapshot of Broad Level Scope

3.1. Key Elements in the Figure 1

The diagram consists of multiple categories influencing failures, including:

1. Piece-to-Piece Variation (Marked X - Not Included)
2. Change Over Time (Marked X – Not Included)
3. Customer Usage
    - Covers truck loading and road conditions.
    - Marked with a ✅, indicating its inclusion in the FMEA analysis.
4. External Environment
    - Factors such as high temperatures (52°C), extreme cold (-40°C), water wading, and flooding.
    - Marked with a ✅, meaning it is considered in the analysis.
5. System Interactions (Marked X - Not Included)
    - LV/HV power distribution
    - Brake system interface

6. Inputs (Marked X - Not Included)
    - HV/LV energy, cooling, wake-up signals, control via CAN.
7. Functions (Marked X - Not Included)
8. Functional Requirements (Marked X - Not Included)
9. Control Factors (Marked X – Not Included)
10. Non-Functional Requirements (Marked X - Not Included)
11. Unintended Outputs (Marked X – Not Included)
12. Outputs
    - Focuses on expected results under various operating and customer conditions.
    - Marked ✅, indicating inclusion in the DFMEA.

3.2. Conclusion on Project Scope

In summary, the project scope inclusions and exclusions are given below:

- The DFMEA includes factors such as Change Over Time, Customer Usage, External Environment, Control Factors, and Outputs.
- The DFMEA excludes Piece-to-Piece Variations, System Interactions, Inputs, Functions, Functional Requirements, Non-Functional Requirements, and Unintended Outputs

This FMEA aims to identify potential failure modes and their effects in the newly designed Battery Electric Truck. The primary objective is to proactively mitigate risks and enhance the safety and reliability of key systems, including Chassis (Axles), Propulsion, Body Control Module, Instrument Cluster, and HVEMS.

3.3. Failure Types Considered

Failures of a function are deducted from the functions. Several types of potential failure modes includes following, but not limited to:

- Loss of function (i.e., inoperable, fails suddenly)
- Degradation of function (i.e., performance loss over time)
- Intermittent function (i.e., operation randomly starts/stops/starts)
- Partial function (i.e., Performance loss)
- Unintended function (i.e., operation at the wrong time, unintended direction, unequal performance)
- Exceeding function (i.e., operation above acceptable threshold)
- Delayed function (i.e., operation after unintended time interval)

Table 1 below provides general definitions of the above failure modes and few examples for these failure modes:

Table 1: Definitions of Failure Modes

Failure Mode	Description
Loss of function	The system becomes completely inoperable, failing suddenly to deliver the intended function. For example, the system fails to deliver any torque to the wheels due to a total inverter failure or a blown fuse in the power supply circuit.
Degradation of Function	The system experiences a gradual reduction in performance over time. For example, torque delivery degrades due to gradual wear of the e-motor bearings, causing increased friction and reduced efficiency in converting electrical energy to mechanical torque. This degradation happens over time and is aggravated over time.
Intermittent Function	The system operates sporadically, starting and stopping unpredictably. For example, torque delivery becomes intermittent because of a loose electrical connector in the 3-phase cable, causing sporadic power interruptions to the motor.
Partial Function	The system delivers the function but at a reduced performance level. For example, the e-motor only delivers 50% of the expected torque due to a malfunctioning phase in the inverter, resulting in partial torque output.
Unintended Function	The system operates when it is not supposed to or produces an undesired effect. For example, torque delivery occurs even if torque request is 0Nm due incorrect signal mapping in the VCU software.
Exceeding Function	The system performs beyond its acceptable limits. For example, torque delivery exceeds the designed threshold, causing wheel slip or loss of traction because of an erroneous high torque demand signal from the VCU.
Delayed Function	The system delivers the function but after an unintended time interval. For example, A delay in torque delivery occurs due to slow response in the VCU software, causing a lag in vehicle acceleration after the driver presses the accelerator pedal.

The report primarily considers customer usage factors such as truck loading, road conditions, and external environments, as outlined in the section 2 above, along with the expected outputs for each operating and customer usage condition.

4. Technical Approach

1. Technical Understanding of the Requirement

- The team begins by thoroughly analysing customer requirements from the RFQ, design specifications, and industry standards.

2. Creation of FMEA Template and Filling Necessary Relevant Data

- A standardized FMEA template Annexure-A [0] is created to document the failure modes, their effects, causes, severity, occurrence, and detection ratings.

3. Boundary Diagram and P-Diagram

- **Boundary Diagram**: Defines the system's components, interactions, and external influences, helping in failure mode identification. A typical boundary diagram is given in Annexure-A [0].
- **P-Diagram:** A P-Diagram (Parameter Diagram) in DFMEA (Design Failure Mode and Effects Analysis) is a structured tool used to define and analyse the inputs, outputs, control factors, and noise factors influencing a system or component's performance. It helps identify potential failure modes by mapping how variations in inputs, noise, or controls could lead to deviations in outputs. Typical P-Diagram is given in Figure 1.

4. Creating FMEA Report for Different Operating Conditions

- The FMEA analysis is extended to different real-world operating conditions, such as:
    - **Truck loading scenarios** (light, medium, full load)
    - **Road conditions** (smooth highways, rough terrain, extreme weather)
    - **External environments** (temperature variations, humidity, corrosion factors)

Please refer to **Section 2** for detailed information on the operating conditions considered in this FMEA report.

5. Review of the FMEA Report

- A cross-functional review is conducted, involving design engineers, safety specialists, quality experts, and customer representatives.

6. Rework (if any) for Generated FMEA Report Based on the Review

- Any gaps or inconsistencies identified during the review process are addressed.
- Additional failure modes, causes, or detection methods may be included based on feedback.

7. Quality Control

- A final validation is performed to ensure compliance with industry standards (e.g., ISO 26262, AIAG-VDA).

5. Systems Covered in the FMEA Report

Following are the systems covered in this FMEA report

1) Electrical System – Body Control Module
2) Propulsion – E-Axle System
3) High Voltage Energy Management System (HV-EMS)
4) Chassis System - Axle System
5) Electrical System – Instrument Cluster

Each category is divided into further several sub-categories.

Beyond P Diagram and B Diagram, reports were generated in the standard template as given in Annexure-A [0].

- The analysis follows the structured DFMEA methodology according to FMEA VDA Handbook (The AIAG VDA methodology was followed as detailed in Failure Mode and Effects Analysis - FMEA Handbook First Edition 2019 by Automotive Industry).
- Failure modes were identified through historical data, expert judgment, and system-level brainstorming.
- Severity, Occurrence, and Detection ratings were assigned based on industry standards (refer Section-10 of this report).
- Risk reduction actions were prioritized using the Action Priority (AP) method as given in Section-11 of this report.

6. System Components

Following are the various components covered in each system considered in this FMEA report.

Components of Chassis (Axles) System:

- Suspension link Assemblies
- Axle Housing
- Spring System
- Dampers
- Wheel Hub Assembly

Components of Electrical System - Body Control Module:

- Processing Unit (Microcontroller & I/O Pins)
- Communications (CAN/LIN Transceivers)

Components of HV Energy Management System (HVEMS):

- Contactors & fuses
- HV battery system
- HV wiring (internal to system)
- Thermal Management System
- Inverter (AC/DC)
- LV Battery System
- LV wiring
- Battery management system (BMS)
- Battery pack cooling inlet/ outlet
- DC/DC cooling inlet/ outlet
- On-board charger cooling inlet/ outlet
- Battery pack vent(s)
- Battery cells/ modules
- Busbars
- Vehicle Charge Port

Components of Propulsion System - E-Axle System:

- VCU
- E-motor/e-axle
- 3 Phase cable
- LV Cables and sensors
- Inverter

Components of Electrical System – Instrument Cluster:

- Processing Unit (Microcontroller & I/O Pins)
- Communications (CAN/LIN Transceivers)

7. Assumptions

Table 2 provides the assumptions considered while preparing the DFMEA sheets.

Table 2: Assumptions on Indian Operating Conditions

Operating Conditions	Assumptions considered for DFMEA
Condition 1	Extreme high temperatures 52 degrees Celsius molten tar is included in condition 4. high winds and radiation are excluded as they are not unique to BETs.
Condition 2	Water wading – worst case will be 1km wading at 40km/hr at 500mm depth. Designing for this will ensure that at speeds 20, 25, 30 and 35km/hr and 200,300, 400mm depth are also covered. Water splashing, tyre traction and torque requirements in wet slippery conditions are unchanged from conventional trucks. The torque delivery of a BET will have the potential to be controlled more precisely than an ICE truck.
Condition 3 a & b	Extreme cold temperatures - -40 degrees Celsius is the worst case, there will be minimal difference in failure mechanism between -20 degrees Celsius and -40 degrees Celsius.
Condition 4	The system DFMEA considers all non-steered axles including 4x2 Haulage, 6x2 / 6x4 Tipper, 8x2 / 8x4 Haulage 10x2/10x4 DTLA Haulage and 6x2 / 6x4 Tractor Trailers.
	The driven part of the axle system are covered in the Propulsion DFMEA.
	Overload GVW plus 50% will also cover failure mechanisms at GVW plus 25% though the distance to failure will be increased at 25%. Operation at GVW rated load is excluded as normal operation.
	Highway and expressway and state roads are paved roads with potholes, expansion joints etc and therefore can be excluded as these are normal operating conditions for all trucks worldwide.
	Dusty, semi-paved roads - rough gravel type roads with large potholes, ruts etc are included.
	River Sand – abrasive and dusty environment is included.
	Salt pan roads - high salt content water splashing, highly corrosive - are included.
	Mining tracks - extreme loading into the suspension system - are included.
	Molten tar - in extreme high temperatures the tar on the road surface will melt and can be sprayed onto the underbody of the truck by the tyres.
	For Instrument Cluster DFMEA GVW, GVW plus 50%, GVW plus 25% is considered as same as it doesn't impact the functionality.
	Radiation- In environments with high electromagnetic activity, electronic components like the truck's instrument cluster can experience disruptions or malfunctions due to stray electromagnetic signals interfering with their operation.
	Where applicable, failure causes will be merged as to avoid duplication of lines.

8. FMEA Rating Criteria

Risk Categorization and Ratings Failure modes were categorized based on:

- Severity (S): Impact of failure on vehicle safety and performance, rated 1-10.
- Occurrence (O): Likelihood of failure happening, rated 1-10.
- Detection (D): Probability of detecting failure before occurrence, rated 1-10.

Example Rating Criteria:

- S = 10: Complete axle failure leading to vehicle control loss.
- O = 7: Moderate likelihood of bearing wear under high loads.
- D = 4: Inspection can detect misalignment but not internal cracks.

Please refer to tables 3, 4, and 5 from the VDA handbook below for rating criteria of Severity, Occurrence and Detection respectively.

Table 3: Severity Ranking

Ranking	Probability	Risk Criteria
10	Very High	Affects safe operation of the vehicle and/or other vehicles, the health of operator or passenger(s) or road users or pedestrians.
9	Very High	Noncompliance with regulations.
8	High	Loss of primary vehicle function necessary for nominal driving expected service life.
7	High	Degradation of primary vehicle function necessary for normal driving during expected service life.
6	Moderate	Loss of secondary vehicle function, comfort or convenience item.
5	Moderate	Degradation of secondary vehicle function, comfort or convenience item.
4	Moderate	Very objectionable appearance, sound, vibration, harshness, or haptics.
3	Low	Moderately objectionable appearance, sound, vibration, harshness, or haptics.
2	Low	Slightly objectionable appearance, sound, vibration, harshness, or haptics.
1	Very Low	No discernible effect.

Table 4: Occurrence Ranking

Rank	Production of FC Occurring	Occurrence criteria DFMEA
10	Extremely High	First application of new technology anywhere without operating experience and/or under uncontrolled operating conditions. No Design verification and/or Validation experience. Standards do not exist, and Best Practices have not yet been determined. Prevention control not able to predict field performance or do not exist.
9	Very High	First use of design with technical innovations or materials within the company. New application or change in duty cycle/operating conditions. No product verification and/or validation experience. Prevention controls not targeted to identify performance to specific requirements.
8	High	First use of design with technical innovations or materials on a new application. New application or change in duty cycle/operating conditions. No product verification and/or validation experience. Few existing standards and best practices, not directly applicable for the design. Prevention controls not a reliable indicator of field performance.
7	High	New design based on similar technology and materials. New application or change in duty cycle/operating conditions. No product verification and/or validation experience. Standards, Best Practices, and design rules apply to the baseline design, but not the innovations. Prevention controls provide limited indication of performance.
6	Moderate	Similar to previous Design, using existing technology and materials. Similar application, with changes in duty cycle or operating conditions. Previous testing or field experience. Standards and Design rules exist but are insufficient to ensure that the failure cause will not occur. Prevention controls provide some ability to prevent the failure cause.
5	Moderate	Detailed changes to previous design, using proven technology and materials. Similar application, duty cycle or operating conditions. Previous testing or field experience, or new design with some test experience related to the failure. Design addresses lessons learned, from previous design. Best Practices re-evaluated for this design but have not yet been proven. Prevention controls capable of finding deficiencies in the product related to the failure cause and provide some indication of performance.
4	Low	Almost identical design with short-term field exposure. Similar application, with minor change in duty cycle or operating conditions. Previous testing or field experience. Predecessor design and changes for new design conform to best practices, standards, and specifications. Prevention controls capable of finding deficiencies in product related to the failure cause and predicted conformance of product design.
3	Low	Detail changes to know design (same application, with minor change in duty cycle or operation conditions) and testing or field experience under comparable operating conditions, or new design with successfully completed test procedure. Design exacted to conform to Standards and Best Practices, considering Lessons Learned from previous designs. Prevention controls capable of finding deficiencies in in the product related to the failure cause and predict conformance of product design.
2	Very Low	Almost identical mature design with long term field exposure. Same application, with comparable duty cycle and operating conditions. Testing or field experience under comparable operating conditions. Design exacted to conform to Standards and Best Practices, considering Lessons Learned from previous designs, with significant margin of confidence. Prevention controls capable of finding deficiencies in in the product related to the failure cause and indicate confidence in design conformance
1	Extremely Low	Failure eliminated through prevention control and failure cause is not possible by design

Table 5: Detection Ranking

Rank	Ability to Detect	Detection Method Maturity	Opportunity for Detection
10	Very Low	Test procedure yet to be developed.	Test Method not defined
9	Very Low	Test method not designed specifically to detect failure mode or cause.	Pass-Fail, Test-to-fall, Degradation Testing
8	Low	New test Method; Not proven.	Pass-Fail, Test-to-fall, Degradation Testing
7	Low	Proven test method for verification of functionality of performance, quality, reliability and durability; planned timing is later in the product development cycle such that test failures may result in production delays for re-design and/or re-tooling.	Pass-Fail testing
6	Moderate	Proven test method for verification of functionality of performance, quality, reliability and durability; planned timing is later in the product development cycle such that test failures may result in production delays for re-design and/or re-tooling.	Test-to-Failure
5	Moderate	Proven test method for verification of functionality of performance, quality, reliability and durability; planned timing is later in the product development cycle such that test failures may result in production delays for re-design and/or re-tooling.	Degradation testing
4	High	Proven test method for verification of functionality or verification of performance, quality, reliability and durability; planned timing is sufficient to modify production tools before release for production.	Pass-Fail testing
3	High	Proven test method for verification of functionality or verification of performance, quality, reliability and durability; planned timing is sufficient to modify production tools before release for production.	Test-to-Failure
2	High	Proven test method for verification of functionality or verification of performance, quality, reliability and durability; planned timing is sufficient to modify production tools before release for production.	Degradation testing
1	Very High	Prior testing confirmed that failure mode or cause cannot occur, or detection method proven to always detect the failure cause.	

9. Action Priority (AP) Assignment

The Action Priority (AP) score is a ranking system introduced in the AIAG-VDA FMEA methodology to prioritize risk reduction efforts. It is determined based on the combination of Severity (S), Occurrence (O), and Detection (D) ratings. Unlike the traditional Risk Priority Number (RPN), which simply multiplies these factors, the AP score categorizes failure modes into three levels: High (H), Medium (M), and Low (L). A High (H) AP score indicates that immediate risk mitigation actions are necessary, whereas Medium (M) AP suggests that action should be considered, and Low (L) AP means that action may not be required unless further evaluation deems it necessary. This approach helps focus efforts on the most critical failure modes, ensuring a structured and effective risk management strategy.

Priority High (H): Highest priority for review and action.

The team needs to either identify an appropriate action to improve prevention and / or detection controls or justify and document why current controls are adequate.

Priority Medium (M): Medium priority for review and action.

The team should identify appropriate actions to improve prevention and / or detection controls, or, at the discretion of the company, justify and document why controls are adequate.

Priority Low (L): Low priority for review and action.

The team could identify actions to improve prevention or detection controls.

For all the DFMEA performed in this study, Action Priority was determined using the AP decision matrix provided in the Table 6. Failures with high severity and occurrence but low detection received high AP. Risk mitigation actions were proposed accordingly.

Table 6: Action Priority Rules

Severity		Occurrence		Detection		AP Level
Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	
9	10	4	10	2	10	H
9	10	4	5	1	1	M
9	10	2	3	7	10	H
9	10	2	3	5	6	M
9	10	2	3	2	4	L
9	10	2	3	1	1	L
9	10	1	1	1	10	L
7	8	6	10	2	10	H
7	8	6	7	1	1	M
7	8	4	5	7	10	H
7	8	4	5	5	6	M
7	8	4	5	2	4	M
7	8	4	5	1	1	M
7	8	2	3	7	10	M
7	8	2	3	5	6	M
7	8	2	3	2	4	L
7	8	2	3	1	1	L
7	8	1	1	1	10	L
4	6	8	10	7	10	H
4	6	8	10	5	6	H
4	6	8	10	2	4	M
4	6	8	10	1	1	M
4	6	6	7	7	10	M
4	6	6	7	5	6	M
4	6	6	7	2	4	M
4	6	6	7	1	1	L
4	6	4	5	7	10	M
4	6	1	5	1	10	L
2	3	8	10	7	10	M
2	3	8	10	5	6	M
1	1	1	10	1	10	L

10. FMEA of Battery Electric Trucks (BETs) Systems

This section provides a detailed overview of the Failure Modes and Effects Analysis (FMEA) conducted for the Battery Electric Truck (BET) systems. RLE has completed five FMEA worksheets, each addressing different subsystems of the BET. The analysis follows the structured approach outlined in the AIAG-VDA FMEA methodology, ensuring a systematic identification of potential failure modes, their causes, effects, and associated risk mitigation strategies.

Refer Table 7 in section 15 of this report for the glossary of terms used in the FMEA worksheets prepared.

Overview of FMEA Worksheets:

The five FMEA worksheets cover the following key BET systems:

1. **Electrical System (Body Control Module)**

- Identifies potential failures in communication interfaces, power distribution, and electronic control functions.
- Includes failures related to CAN/LIN transceivers, wiring harness faults, and BCS software malfunctions.

Logic Explanation Table:

For this project		Ownership	Explanation
Level	Sub-System		
Next Higher Level	Electrical	OEM	The System Level DFMEA identifies the high-level failure modes for example, degraded performance of Body Control Module, loss of communication.
Focus Element	Body Control Module	OEM	
Next Lower level	e.g. Processing unit (microcontroller, Input/output pins), CAN/LIN transceivers	Supplier	

For the Supplier / Component DFMEA - Out of scope		Ownership	Explanation
Level	Sub-System		
Next Higher Level	Electrical	OEM	The Component Level DFMEA identifies the mechanisms which cause the failure modes at system level.
Focus Element	Body Control Module	Tier 1 Supplier	
Next Lower Level	e.g. Processing unit (microcontroller, Input/output pins), CAN/LIN transceivers	Tier 2 Supplier	

B-Diagram of Body Control Module:

Please refer to the FMEA worksheet link given below for the B-diagram:

P-Diagram of Body Control Module:

Please refer to the FMEA worksheet link given below for the P-diagram:

FMEA Worksheet of Body Control Module:

Link to DFMEA of Electrical System-Body Control Module

2. Chassis System (Axle System)

- Covers mechanical failures such as axle fatigue, suspension link wear, and bearing failures under extreme loading conditions.
- Considers the impact of road conditions, temperature variations, and overload scenarios.

Logic Explanation Table:

For this project		Ownership	Explanation
Level	**Sub-System**		
Next Higher Level	Chassis	OEM	The System Level DFMEA identifies the high-level failure modes e.g. breaks, deforms, degrades etc
Focus Element	Axle System	OEM	
Next Lower level	e.g. Axle Housing, Suspension Link Assemblies, Spring System, Anti-Roll bar system	Supplier	

For the Supplier / Component DFMEA - Out of scope		Ownership	Explanation
Level	**Sub-System**		
Next Higher Level	Axle System	OEM	The Component Level DFMEA identifies the mechanisms which cause the failure modes at system level e.g. weld failure, fatigue, leaks, age hardening etc
Focus Element	Axle Housing	Tier 1 Supplier	
Next Lower Level	e.g. Axle Casting Seals Bearings Brackets Fixings etc	Tier 2 Supplier	

B-Diagram of Chassis System:

Please refer to the FMEA worksheet link given below for the B-diagram:

P-Diagram of Chassis System:

Please refer to the FMEA worksheet link given below for the P-diagram:

FMEA Worksheet of Chassis System (Axle System):

Link to DFEMA of Chassis System-Axle System

3. Propulsion System – E-Axle System

- Evaluates risks related to the e-motor, inverter, and power electronics.
- Addresses potential failures in motor torque delivery, thermal management, and inverter control strategies.

Logic Explanation Table:

<table>
<tr><th colspan="2">For this project</th><th rowspan="2">Ownership</th><th rowspan="2">Explanation</th></tr>
<tr><th>Level</th><th>Sub-System</th></tr>
<tr><td>Next Higher Level</td><td>HV System</td><td>OEM</td><td rowspan="3">The System Level DFMEA identifies the high-level failure modes</td></tr>
<tr><td>Focus Element</td><td>Propulsion System</td><td>OEM</td></tr>
<tr><td>Next Lower level</td><td>VCU, Inverter, 3 phase cable, CAN messages sensor cables, e-axle, e-motor, brake/calliper actuators (1 option), wheel ends and rotors (1 option)</td><td>Supplier</td></tr>
</table>

<table>
<tr><th colspan="2">For the Supplier / Component DFMEA
- Out of scope</th><th rowspan="2">Ownership</th><th rowspan="2">Explanation</th></tr>
<tr><th>Level</th><th>Sub-System</th></tr>
<tr><td>Next Higher Level</td><td>HV System</td><td>OEM</td><td rowspan="3">The Component Level DFMEA identifies the mechanisms which cause the failure modes at system level e.g. electronic component failure (connector, transceiver, microprocessor), ECU connector failure, terminal failure etc</td></tr>
<tr><td>Focus Element</td><td>Propulsion System</td><td>Tier 1 Supplier</td></tr>
<tr><td>Next Lower Level</td><td>ECU PCB, harness sub-component, connector etc</td><td>Tier 2 Supplier</td></tr>
</table>

B-Diagram of Chassis System:

Please refer to the FMEA worksheet link given below for the B-diagram:

P-Diagram of Chassis System:

Please refer to the FMEA worksheet link given below for the P-diagram:

FMEA Worksheet of Propulsion System – E-Axle System:

[Link to DFMEA of Propulsion System (E-Axle System)]

4. HV Energy Management System (HVEMS)

- Assesses failures in battery performance, power distribution, and high-voltage safety mechanisms.
- Examines failure scenarios such as thermal runaway, overcharging, and power loss.

Logic Explanation Table:

For this project		Ownership	Explanation
Level	**Sub-System**		
Next Higher Level	Chassis	OEM	The System Level DFMEA identifies the high-level failure modes e.g. overheats, deforms, degrades etc
Focus Element	HV energy management system	OEM	
Next Lower level	e.g. HV battery system, on-board charger, DC/DC converter, and HV power distribution unit, as well as their components	Supplier	

For the Supplier / Component DFMEA - Out of scope		Ownership	Explanation
Level	**Sub-System**		
Next Higher Level	HV energy management system	OEM	The Component Level DFMEA identifies the mechanisms which cause the failure modes at system level e.g. fatigue, leaks etc
Focus Element	Battery, OBC, DCDC, and HVPDU	Tier 1 Supplier	
Next Lower Level	e.g. BMS, sensors, cables, fuses, connectors, contactors etc.	Tier 2 Supplier	

B-Diagram of High Voltage Energy Management System (HVEMS):

Please refer to the FMEA worksheet link given below for the B-diagram:

P-Diagram of High Voltage Energy Management System (HVEMS):

Please refer to the FMEA worksheet link given below for the P-diagram:

FMEA Worksheet of HV Energy Management System (HVEMS):

[Link to DFMEA of HV Energy Management System]

5. Electrical System – Instrument Cluster

- Focuses on failures in driver interface components such as instrument clusters, control switches, and HMI systems.
- Includes risks associated with software malfunctions and display failures.

Logic Explanation Table:

For this project		Ownership	Explanation
Level	**Sub-System**		
Next Higher Level	Electrical	OEM	The System Level DFMEA identifies the high-level failure modes for example, degraded performance of Instrument Cluster, loss of communication.
Focus Element	Instrument Cluster	OEM	
Next Lower level	e.g. Processing unit (microcontroller, Input/output pins), CAN/LIN transceivers	Supplier	

For the Supplier / Component DFMEA - Out of scope		Ownership	Explanation
Level	**Sub-System**		
Next Higher Level	Electrical	OEM	The Component Level DFMEA identifies the mechanisms which cause the failure modes at system level.
Focus Element	Instrument Cluster	Tier 1 Supplier	
Next Lower Level	e.g. Processing unit (microcontroller, Input/output pins), CAN/LIN transceivers	Tier 2 Supplier	

B-Diagram of Electrical System – Instrument Cluster:

Please refer to the FMEA worksheet link given below for the B-diagram:

P-Diagram of Electrical System – Instrument Cluster:

Please refer to the FMEA worksheet link given below for the P-diagram:

FMEA Worksheet of Electrical System – Instrument Cluster:

[Link to DFMEA of Electrical System (Instrument Cluster)]

11. Summary

The Failure Modes and Effects Analysis (FMEA) conducted for the Battery Electric Truck covers key systems, including Chassis (Axle System), Propulsion System, Body Control Module, High Voltage Energy Management System, and Instrument Cluster. The analysis systematically identified potential failure modes, assessed their impact, and prioritized corrective actions using the Action Priority (AP) methodology. The study followed a structured approach, incorporating historical data, expert evaluations, and industry standards such as ISO 26262. The risk assessment process categorized failure modes based on severity, occurrence, and detection ratings. The findings from this report highlight key high-risk failure modes, their Action Priority (AP) scores, and proposed design improvements to enhance vehicle safety and performance. Future steps include implementing corrective measures, monitoring their effectiveness, and conducting periodic FMEA reviews to ensure long-term product reliability and safety.

This FMEA report is generic in nature which is common to all battery electric trucks working in India under extreme operating conditions and is not specific to any particular model of BET. OEMs and other users adopting this FMEA may need to customize their DFMEA analysis based on the actual components, systems, and configurations fitted in their specific vehicle models of trucks.

12. Glossary of Terms

Table 7: Glossary of Terms

Term	Explanation
Breaks	The item suddenly separates into multiple pieces. The detailed mechanisms for this shall be considered in the component level DFMEA.
Deforms	The geometry of the item is changed. e.g. it bends under excess loading the detailed mechanisms for this shall be considered in the component level DFMEA.
Fails prior to reaching design life	The item breaks before reaching its intended life e.g. 20,000km not 100,000km. The detailed mechanisms for this shall be considered in the component level DFMEA.
Degrades	The performance of the item changes over time e.g. loss of damping performance or spring stiffness. The detailed mechanisms for this shall be considered in the component level DFMEA.
Geometry not maintained	The suspension geometry is not maintained. The detailed mechanisms for this shall be considered in the component level DFMEA.
Clearance not maintained	The clearance between components is not maintained. The detailed mechanisms for this shall be considered in the component level DFMEA.
Dynamic clearance not maintained	As the suspension moves through its range of motion the clearances between components are not maintained. The detailed mechanisms for this shall be considered in the component level DFMEA.
Efficiency	The performance of the system is not up to the mark. System can deliver but with less accuracy and not full functionality. The detailed mechanism for this shall be considered in the component level DFMEA and during the component level DV test.
Loss of function	The system becomes completely inoperable, failing suddenly to deliver the intended function. For example, the system fails to deliver any torque to the wheels due to a total inverter failure or a blown fuse in the power supply circuit.
Degradation of Function	The system experiences a gradual reduction in performance over time. For example, torque delivery degrades due to gradual wear of the e-motor bearings, causing increased friction and reduced efficiency in converting electrical energy to mechanical torque. This degradation happens over time and is aggravated over time.
Intermittent Function	The system operates sporadically, starting and stopping unpredictably. For example, torque delivery becomes intermittent because of a loose electrical connector in the 3-phase cable, causing sporadic power interruptions to the motor.

Term	Explanation
Partial Function	The system delivers the function but at a reduced performance level. For example, the e-motor only delivers 50% of the expected torque due to a malfunctioning phase in the inverter, resulting in partial torque output.
Unintended Function	The system operates when it is not supposed to or produces an undesired effect. For example, torque delivery occurs even if torque request is 0Nm due incorrect signal mapping in the VCU software.
Exceeding Function	The system performs beyond its acceptable limits. For example, torque delivery exceeds the designed threshold, causing wheel slip or loss of traction because of an erroneous high torque demand signal from the VCU.
Delayed Function	The system delivers the function but after an unintended time interval. For example, A delay in torque delivery occurs due to slow response in the VCU software, causing a lag in vehicle acceleration after the driver presses the accelerator pedal.
VCU	Vehicle Control Unit, Master Controller of the Propulsion system responsible for processing sensor inputs, torque demands, managing torque delivery etc.
MCU	A microcontroller or microcontroller unit is a small computer on a single integrated circuit. A microcontroller contains one or more CPUs along with memory and programmable input/output peripherals. It is a common part used in embedded ECUs
ECU	An electronic control unit, also known as an electronic control module, is an embedded system in automotive electronics that controls one or more of the electrical systems or subsystems in a car or other motor vehicle.
EDS	Electrical Distribution Systems - refers to all related components for wiring harness: cables, terminals, connectors, insulation type. Applies to both HV and LV

13. Acknowledgements

The authors of this DFMEA report would like to express their sincere gratitude to all the contributors who played a key role in its development. Their expertise, insights, and collaboration were instrumental in ensuring a comprehensive risk assessment for the Battery Electric Truck (BET) systems.

We acknowledge and appreciate the valuable contributions from the following team members:

RLE India:

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5.	Prof. C.S. Shankar Ram	Principal Investigator
6.	Mr. Thangaraj R	Truck After Market Expert
7.	Mr. Ganeshan Mani	Ex. Principal Project Officer

14. REFERENCES

1. ISO 26262: Road vehicles - Functional safety - 2018
2. AIAG & VDA Failure Mode and Effects Analysis (FMEA) Handbook

15. ANNEXURE-A

1. FMEA Template:

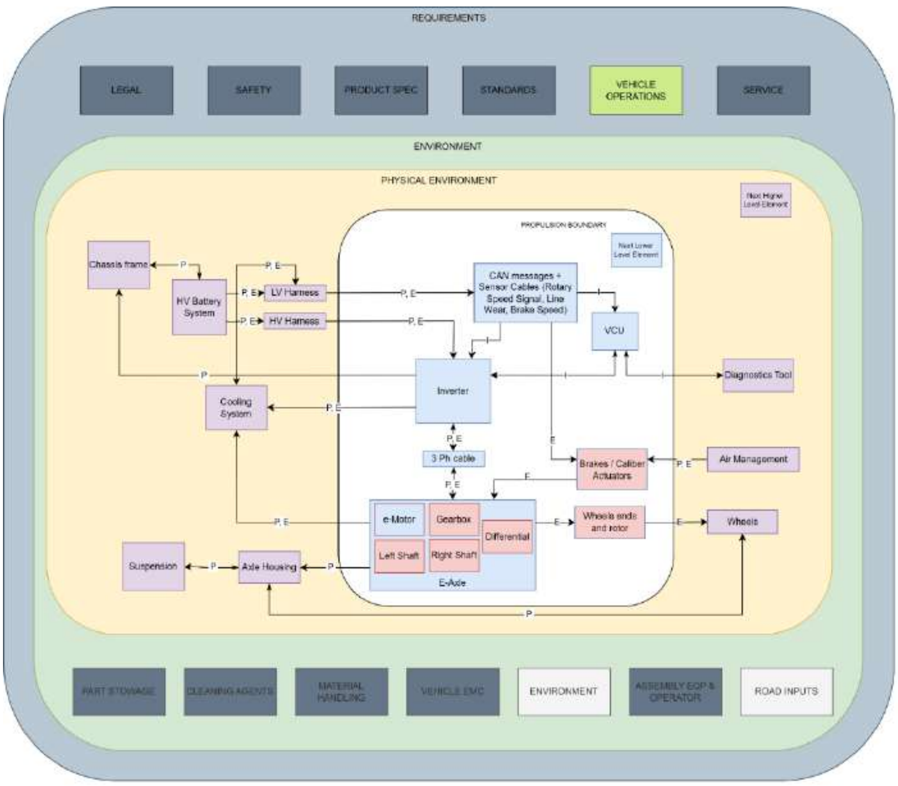
Design Failure Mode and Effects Analysis (Design FMEA)

Company Name:		Subject:		DFMEA ID Number:	
Engineering Location:		DFMEA Start Date:		Design Responsibility:	
Customer Name:		DFMEA Revision Date:		Confidentiality Level:	
Model Year(s)/Program(s):		Cross-Functional Team:			

Worksheet

Next Higher Level	Focus Element	Next Lower Level	Next Higher Level Function and Requirement (Vehicle)	Focus Element Function and Requirement	Next Lower Level Function and Requirement	Failure Effect (FE) to the Next Higher Level Element	Severity (S) of Failure Effect	Classification	Failure Mode (FM) of the Focus Element	Failure Cause (FC) of the Next Lower Element or Characteristic	Current Prevention Controls (PC) of FC	Occurrence (O) of FC	Current Detection Controls (DC) of FC or FM	Detection (D) of FC/FM	AP	Recommended Action	Action Type	Responsible Person's Name	Target Completion Date	Status	Action Taken with Pointer to Evidence	Completion Date	Revised Severity (S)	Revised Occurrence (O)	Revised Detection (D)	Revised AP

2. Typical boundary diagram used during FMEA analysis:



P - Physical interactions such as welded, bolted, clamped, fits, clearances, etc.
I - Information transfers such as CAN signals, Sensor signals, RF signals, etc.

E - Energy transfers such as torque, heat, current, vibration, etc.
M - Material exchanges or transfers such as cooling fluid, exhaust gases, brake fluid, wear, etc.

Figure 2: Typical Boundary Diagram used in FMEA

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