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# Electric Bus Systems in India: Technology, Performance and Maintenance

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**Abstract - The rapid electrification of public transportation in India represents a critical transition toward sustainable mobility, reduced greenhouse gas emissions, and improved urban air quality. Electric buses (E-buses) are emerging as a key component of this transformation; however, their long-term technical reliability, battery degradation behaviour, and lifecycle performance under Indian operating conditions remain insufficiently understood. This research presents a comprehensive multi-scale analysis of electric bus systems, focusing on battery degradation modelling, mechanical reliability assessment, seasonal performance variation, and lifecycle optimization within the Indian context. The study investigates lithium-ion battery chemistries commonly used in Indian electric buses, including Lithium Iron Phosphate (LFP) and Nickel Manganese Cobalt (NMC), with emphasis on depth of discharge (DoD), C-rate effects, equivalent full cycle (EFC) counting, and thermal stress impacts. A predictive degradation framework is developed to estimate state of health (SoH) under variable duty cycles and climatic conditions. Results indicate that temperature variations above 35°C and high C-rate charging significantly accelerate capacity fade and internal resistance growth, directly influencing operational range and battery lifespan. Mechanical reliability analysis is conducted through Failure Mode and Effects Analysis (FMEA) and stress evaluation of suspension, axle, braking, and chassis systems. The increased vehicle mass due to battery integration is shown to elevate suspension and structural fatigue risks compared to conventional diesel buses. Seasonal performance evaluation highlights summer-induced thermal derating, monsoon-related electrical ingress risks, and winter-associated capacity reduction. A techno-economic assessment incorporating total cost of ownership (TCO) and lifecycle cost modelling demonstrates that despite higher initial acquisition costs, optimized charging strategies, predictive maintenance, and trained driver intervention significantly improve economic viability. The research further integrates preventive maintenance frameworks, telematics-based diagnostics, and driver training impacts on energy efficiency. The findings contribute to the development of a predictive reliability and lifecycle optimization framework tailored to Indian operating environments. This study provides actionable insights for policymakers, fleet operators, and manufacturers to enhance electric bus deployment strategies, improve battery longevity, and ensure sustainable public transportation systems.**

**Keywords - Electric Buses (E-buses), Lithium-ion Battery Degradation, State of Health (SoH) Estimation, Lifecycle Optimization, Sustainable Public Transportation.**

## I. INTRODUCTION

### Background of Electric Bus Electrification in India

India’s public transportation system plays a critical role in enabling economic productivity, social mobility, and urban sustainability. With rapid urbanization, increasing population density, and expanding metropolitan regions, public bus networks have become the backbone of affordable mass transit. However, the conventional diesel-powered bus fleet has historically contributed significantly to urban air pollution, greenhouse gas emissions, and fuel import dependency. [11]

The electrification of public bus transportation in India has emerged as a strategic response to environmental, economic, and energy security challenges. The transition aligns with India's broader commitment to climate change mitigation under international agreements and national decarbonization targets. The transport sector accounts for a substantial proportion of urban particulate emissions (PM2.5), nitrogen oxides (NOx), and carbon dioxide ($CO_2$), with diesel buses being one of the major contributors in densely populated cities.[9]

Electric buses (E-buses), powered by lithium-ion battery systems, provide zero tailpipe emissions and significantly lower noise levels compared to internal combustion engine (ICE) buses. The electrification initiative has gained momentum due to policy support such as the Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) scheme, Production Linked Incentive (PLI) for Advanced Chemistry Cell (ACC) batteries, and various state-level electric vehicle policies.

Major Indian cities such as Delhi, Mumbai, Bengaluru, Hyderabad, Ahmedabad, and Pune have initiated large-scale procurement and deployment of electric buses under centralized and state-supported tenders. Programs such as the PM e-Bus Sewa initiative have further accelerated adoption by providing viability gap funding and operational subsidies. As a result, India has witnessed a rapid increase in the number of electric buses deployed in both city and limited intercity routes.

From a technological perspective, most electric buses operating in India utilize lithium-ion battery chemistries such as Lithium Iron Phosphate (LFP) and Nickel Manganese Cobalt (NMC). LFP batteries are preferred for their thermal stability and safety performance, particularly suitable for Indian climatic conditions where ambient temperatures frequently exceed 40°C during summer months. Battery capacities typically range from 250 kWh to 450 kWh for 9-meter and 12-meter city buses, with ranges of 150–250 km per charge depending on duty cycles, passenger load, HVAC usage, and traffic congestion.[10][11]

Despite these advancements, the electrification of buses introduces new engineering complexities. Unlike diesel buses, electric buses rely on high-voltage power electronics, battery management systems (BMS), regenerative braking, and thermal management systems. Additionally, the increased curb weight due to battery packs influences suspension systems, axle loads, and structural integrity.

Working in the electric bus field provides direct exposure to operational challenges such as:

- Battery overheating during peak summer
- Reduced range during extreme temperatures
- HVAC-related energy consumption
- Suspension wears due to increased gross vehicle weight (GVW)
- Charging infrastructure constraints
- Preventive maintenance adaptation requirements

These operational realities highlight the need for systematic research addressing performance degradation, reliability engineering, and lifecycle optimization tailored to Indian conditions.

**Research Motivation**

The primary motivation for this research arises from the intersection of policy ambition and operational complexity. While India is aggressively expanding its electric bus fleet, empirical understanding of long-term battery degradation, mechanical reliability, seasonal performance variations, and economic sustainability remains limited.[11]

From field experience, several critical issues are observed:

- Battery degradation varies significantly based on driving patterns, charging protocols, and ambient temperatures.
- High C-rate fast charging, though operationally convenient, accelerates battery wear.
- Suspension and structural components experience higher stress due to battery mass.
- Range anxiety and driver behaviour directly impact fleet efficiency.
- Preventive maintenance frameworks for electric buses are still evolving.

There is a clear gap between theoretical expectations and real-world performance. For instance, manufacturer-stated battery lifespan of 6–8 years may not align with actual degradation trends under

Indian duty cycles involving stop-and-go traffic, heavy passenger load, and high thermal stress.

**The research is further motivated by the need to:**

- Develop predictive degradation models specific to Indian climatic and operational conditions.
- Quantify mechanical reliability risks introduced by electrification.
- Optimize charging and operational strategies to extend battery life.
- Reduce total cost of ownership (TCO) through evidence-based fleet management.

Given professional involvement in the electric bus field, this research integrates practical insights with rigorous analytical modelling, ensuring both academic relevance and industry applicability.

**Problem Statement**

- Although electric buses offer environmental and operational advantages, their large-scale deployment in India faces unresolved technical and economic challenges. The key problems can be summarized as follows:[11]
- Uncertainty in Battery Lifespan
- Battery degradation under high temperature, variable depth of discharge (DoD), and fast charging remains insufficiently quantified.
- Reliability Risks Due to Increased Vehicle Mass
- The integration of high-capacity battery packs increases gross vehicle weight, potentially accelerating suspension fatigue and structural stress.
- Seasonal Performance Variability
- Indian climatic diversity (summer heat, monsoon humidity, winter cold) significantly affects battery performance and electrical reliability.
- Limited Predictive Maintenance Frameworks
- Current maintenance practices are often reactive rather than predictive, leading to unplanned downtime.
- Economic Viability Concerns
- High upfront capital costs require optimized lifecycle management to ensure long-term financial sustainability.

Therefore, the central problem addressed in this thesis is:

"How can electric bus systems be technically optimized and reliability-enhanced under Indian operating conditions to maximize battery life, mechanical durability, and lifecycle economic efficiency?"

**Research Objectives**

The primary objective of this research is to develop an integrated performance, degradation, and reliability optimization framework for electric buses operating in India.

**Specific objectives include:**

- To analyze lithium-ion battery degradation mechanisms under real-world duty cycles.
- To model equivalent full cycles (EFC) and C-rate impacts on battery health.
- To evaluate mechanical reliability of suspension, axle, and chassis systems under increased load.
- To assess seasonal impacts on battery and power electronics performance.
- To design a predictive maintenance strategy integrating telematics data.
- To conduct techno-economic lifecycle cost analysis.
- To propose optimization strategies for fleet operators and policymakers.

## II. LITERATURE REVIEW

The electrification of the transportation sector is accelerating globally, driven by the urgent need to reduce greenhouse gas emissions and dependence on fossil fuels. Transportation accounts for a significant portion of final energy demand, with a vast majority historically supplied by non-renewable sources [1]. Within this context, electric buses have emerged as a cornerstone of sustainable urban mobility. Unlike personal electric vehicles (EVs), E-buses operate under rigorous, high-duty cycles that impose severe stress on energy storage systems. The core motivation for this research lies in the economic and operational vulnerability of E-buses: the battery pack represents the single most expensive component, and its degradation directly impacts the vehicle's remaining useful life (RUL) and the fleet operator's return on investment.

Despite the proliferation of E-bus pilot programs, significant challenges impede widespread adoption, particularly in developing markets like India where grid reliability and extreme thermal conditions exacerbate technical failures. A critical problem is the insufficiency of existing battery management strategies, which often rely on simplistic heuristic models that fail to account for the complex, non-linear nature of lithium-ion battery aging under dynamic loads [2]. Furthermore, current fleet routing algorithms frequently treat the power grid as an infinite bus, neglecting the impact of simultaneous high-power charging on distribution network stability and voltage deviation [3].

**To address these deficiencies, this paper makes the following contributions:**

- It synthesizes state-of-the-art battery degradation mechanisms, contrasting traditional cycle-counting methods with novel diffusion-based generative models for capacity loss prediction.
- It analyzes the symbiotic relationship between charging infrastructure and grid health, highlighting how uncoordinated charging increases energy losses and infrastructure inequity.
- It proposes an integrated "Health-Aware Fleet Scheduling Framework" that simultaneously optimizes for route completion, battery longevity, and grid stability.

## Related Work

### Data-Driven Battery Degradation Modeling

Understanding battery health is paramount for E-bus reliability. Recent literature has shifted from electrochemical models to data-driven approaches. Traditional heuristic models often estimate degradation based on simple cycle counting or throughput, but these often lack validation against real-world aging data [2]. A significant advancement is the introduction of deep learning techniques. For instance, the DiffBatt model utilizes conditional and unconditional diffusion models to predict battery capacity loss and synthesize degradation curves [4]. This approach addresses the data scarcity issue by generating synthetic aging profiles, achieving lower root mean square error (RMSE) compared to traditional models. Similarly, neural network-based degradation (NNBD) models have been developed to quantify aging factors more precisely than linear cost functions, allowing for better integration into microgrid scheduling [5]. These studies highlight that accurate degradation modeling is a prerequisite for any robust E-bus operational strategy.

### Grid Interaction and Charging Infrastructure

The deployment of E-buses cannot be viewed in isolation from the power grid. Large-scale charging creates substantial load uncertainties, leading to voltage deviations and energy losses in distribution networks. Research indicates that incorporating battery degradation costs into grid scheduling—through multi-objective frameworks—can minimize monetary costs while improving network performance [3]. Moreover, the physical location and accessibility of charging infrastructure are critical. Studies utilizing GIS data have shown that the popularity and utilization of charging stations are strongly correlated with urban context and amenities, yet access remains inequitable [6]. In some urban environments, charging infrastructure is heavily skewed against low-income neighborhoods, suggesting that E-bus depot planning must consider socio-economic equity alongside technical grid constraints [7]. The "WEcharge" concept further proposes democratizing infrastructure through resource-matching algorithms, which could be adapted for shared heavy-duty charging depots [8].

### Operational Fleet Management and Reliability

Operational reliability involves balancing immediate service demands with long-term asset preservation. Research into fleet routing problems (VRP) has evolved to include dynamic battery degradation constraints. By monitoring the depth-of-discharge (DoD) boundaries, operators can significantly extend the cycle lifetime of the fleet without compromising route completion [1]. However, conflicting incentives exist; maximizing short-term profit often requires high-rate charging that accelerates degradation. Reinforcement learning policies have been demonstrated to reconcile these conflicts by learning charging strategies that prolong service life while alleviating grid stress [9]. Additionally, in systems with pulse power loads, such as shipboard or heavy-duty bus systems, heuristic energy management strategies can adaptively split power demand to protect storage elements from high ramp rates, a concept directly transferable to E-bus acceleration profiles [10].

## III. ELECTRIC BUS SYSTEM ARCHITECTURE

Detailed technical standard guide for 7 m, 9 m, and 12 m Electric Buses in India — based on current Indian standards (CMVR/AIS) and specifications commonly used in government tenders/procurement (e.g., PM e-Bus Sewa, Urban Bus Specifications) with emphasis on electric-bus-specific requirements. [1]

**Applicable Regulatory & Technical Standards (India)**
**Mandatory Compliance**

- Automotive Industry Standards (AIS):
- AIS 052 (Rev1) – Bus Body Code (overall body design, structure, safety).
- AIS 153 – Standardisation of fully built buses (updated Sept 2025; applies to electric buses too with additional requirements for safety, exits, fire systems).
- Ministry of Road Transport and Highways (MoRTH) / CMVR: CMVR rules require type approval and homologation with appropriate AIS standards.
- Bureau of Indian Standards (BIS): Supplementary material & electrical insulation standards (IS series).
- ITS / Telematics Standard: AIS 140 — GPS, GNSS and telematics devices mandated in all public passenger buses per MoRTH.

**Core Technical Specification Template (7 m, 9 m, 12 m Electric Buses)**

These are typical specifications from government tender documents/configurations that align with CMVR + AIS codes, including electric system requirements. [1] [4]

Dimensions & Basic Physical Parameters

| Parameter | 7 m Bus | 9 m Bus | 12 m Bus |
|---|---|---|---|
| Overall Length | ~7000 mm (± tolerance) | ~9000 mm | ~12000 mm |
| Wheelbase | ~4200–4500 mm | ~5200–5500 mm | ~6200–6500 mm |
| Overall Width | ~2300–2500 mm | ~2300–2500 mm | ~2500–2600 mm |
| Overall, Height | ~3100–3400 mm | ~3200–3400 mm | ~3300–3500 mm |
| Floor Height | 650 mm or 900 mm option | 900 mm | 900 mm (standard) |
| Turning Radius | ~6.8–7.2 m | ~8.3–8.7 m | ~10–11 m |
| GVW (Approx.) | ~8–10 t | ~10–12 t | ~17–19.5 t |

Floor heights and low-floor accessibility are increasingly standard per MoRTH/urban bus specs.

**Body Design & Structure (AIS 052 + CMVR)[1]**
**Body Frame & Materials:**

- Structure designed in accordance with AIS 052 (bus body code) for strength, corrosion protection, load path, crash resistance.
- Main members — high tensile steel / cold-formed sections
- Outer panels — GI/aluminium/FRP with corrosion protection & suitable surface finish.
- Doors & Emergency Exits:
- 12 m & 9 m: 2 passenger doors (main + rear), power-operated where required; wheelchair ramp at main door.
- 7 m: Typically, 1 passenger door + driver door.
- Emergency exit positions, roof hatches, escape windows per AIS 052 & AIS 153 requirements

(minimum exits determined by length/occupancy).

- Gangway & Seating:
- Passage/gangway clear width per bus size (based on Urban Bus Specifications).
- Seats anchored to body structure, crash-worthy and fire-resistant as per bus codes.

**Electric Powertrain & High-Voltage Systems**

**Traction Motor & Controller:**

- High-efficiency motor (PMSM/induction type) sized to provide >5 kW/ton power-to-weight ratio for safe, urban operations.

**Battery System:**

- Lithium-ion / $LiFePO_4$ / NMC battery pack with robust BMS.
- Rated energy sized for required range (provider design); fast-charging capability usually mandatory.
- Cooling & safety systems per AIS requirements.

**Charging:**

- On-board/off-board charging compatibility — DC fast charging (CCS2 / GB/T / India standard) per IEC standards, and 415 V AC for depot charging.

**Electrical Safety:**

- High-voltage interlocks, emergency cutoff switches, insulation monitoring.
- All high-voltage wiring protected and routed away from heat sources per bus design rules.

**Suspension, Brakes & Steering**

- Suspension: Front independent / I-beam and rear air suspension for comfort; comply with UBS/Bus code.

- Brakes: Dual circuit full air system, ABS (where required) plus parking brake.
- Steering: Power steering with safe turning and control.
- Speed Limitation: As per commercial vehicle regulations (AIS-018 if fitted).

**Safety & Passenger Comfort (AIS 153)**

AIS 153 has updated safety compliance for fully built buses including electric buses. Key focus areas:

- NVH Limits — Interior noise & vibration control for comfort.
- Fire Safety — Detection (FDAS) mandatory; suppression systems where applicable (AIS-135).
- Lighting — Interior/exterior illumination minimum lux levels per standards.
- Exits & Emergency Egress — Defined based on bus length.

**ITS & Telematics (AIS 140)**

**Buses must include:**

- GPS tracking unit compliant with AIS 140
- Fleet management, real-time passenger information displays
- CCTV with storage per specification.

**Testing & Homologation**

- Type approval from accredited agencies (ARAI/ICAT/CIRT).
- Prototype testing per CMVR & AIS norms including structural, electrical, braking, and fire safety tests.

## IV. BATTERY PERFORMANCE AND DEGRADATION ANALYSIS

table showing the main types of electric bus batteries, their chemistries, and leading battery makers used in electric buses globally and in India [3]

| Electric Bus Battery Types & Chemistries | | | | |
|---|---|---|---|---|
| Battery Type | Full Name | Key Features | Advantages | Common Use in E-Buses |
| LFP | *Lithium Iron Phosphate* | Iron-based cathode | High thermal & safety, long cycle life, low cost | Most common for city & commercial buses |

| | | | | |
|---|---|---|---|---|
| NMC | *Nickel Manganese Cobalt Oxide* | Nickel-based cathode | Higher energy density (more range) | Some premium buses |
| LTO | *Lithium Titanate Oxide* | Titanium in anode | Fast charging & very long life | Niche/rapid-charge applications |
| Solid-state / emerging | *Advanced solid electrolytes* | Still in R&D | Higher energy & safety | Future tech (not yet mainstream) |

| Examples of Battery Use in Popular E-Buses | | | | |
|---|---|---|---|---|
| Electric Bus Model | Battery Type | Battery Capacity | Typical Chemistry | Source |
| MG iEV12 | BEV battery pack | 417–489 kWh | LFP / Lithium-ion | cmv360 |
| Alexander Dennis Enviro400EV (early gen) | BEV pack | ~320 kWh | LFP / NMC (later) | Cmv360 |
| Yutong E10/E12 | BEV pack | 350–422 kWh | LFP | Cmv360 |
| Typical Indian E-bus (e.g., Switch Mobility) | Standard pack | ~300–450 kWh | LFP common | Cmv360 |
| Tata Star bus EV | BEV pack | ~124–245 kWh | Li-ion (NMC in some) | Cmv360 |

**Battery Cycle Counting and C-Rate Analysis**
**Counting of Battery Cycles**

Battery warranty in electric buses is generally specified either in terms of the total number of charges–discharge cycles (full equivalent cycles) or in years of operation. A battery cycle is defined as one complete discharge and recharge process under specified operating conditions such as depth of discharge (DoD), charge/discharge rate (C-rate), and temperature.[3]

In real-world electric bus operations, load profiles are dynamic and do not always allow the battery to discharge from 100% state of charge (SoC) to 0% SoC in a single cycle. Instead, batteries often operate within partial SoC windows. Therefore, the concept of Equivalent Full Cycles (EFC) or equivalent number of cycles is introduced to standardize battery degradation assessment.

The equivalent number of cycles for a given DoD is defined as the number of cycles that would be equivalent to a full 100% SoC discharge–charge cycle This method allows partial discharge cycles to be converted into standardized full-cycle equivalents for accurate lifetime estimation.

For example, consider a battery operating under the following SoC profile:

- Initial SoC: 80% (20% DoD)
- Discharged to: 40% SoC (60% DoD)
- Recharged to: 60% SoC (40% DoD)

In this case, the maximum depth of discharge reached during the cycle is 60%. The equivalent number of cycles (Neq) can be calculated by summing the partial DoD contributions over time and normalizing them with respect to a full 100% DoD cycle.

This methodology is illustrated in Figure A2 (Motapon et al., 2020), where partial discharge and charge segments are aggregated to compute the equivalent full-cycle count .[3]

**Charge and Discharge Rate (C-Rate)**

The C-rate is a measure of the rate at which a battery is charged or discharged relative to its nominal capacity. It is calculated as:[3]

$$\text{C-rate} = \frac{Power\ (kW)}{\text{Battery Capacity (kWh)}}$$

**Charging Rate**

The charging rate depends on charger power and battery capacity. For example, consider a 15-kWh battery pack:
1C Charging Rate:
Charging power = 15 kW
Charging time = 1 hour
A 15 kW charger is required.
2C Charging Rate:
Charging power = 30 kW
Charging time = 0.5 hours
A 30 kW charger is required.
Charging at a C-rate less than 1C is typically referred to as slow charging, while charging at a C-rate equal to or greater than 1C is considered fast charging. Higher C-rates can reduce charging time but may accelerate battery degradation due to increased thermal stress.

**Discharge Rate**

Similarly, the discharge rate depends on the power demanded by the vehicle relative to battery capacity.

For a 15-kWh battery pack:

- If the vehicle requires 15 kW of power, the battery is discharged at 1C, resulting in a complete discharge in approximately 1 hour.
- If the vehicle requires 60 kW of power, the battery is discharged at 4C, meaning the battery would theoretically discharge in 0.25 hours (15 minutes), assuming constant load.

Higher discharge C-rates lead to increased internal resistance losses and thermal buildup, which can significantly impact battery lifespan and performance.

**Implications for Electric Bus Operations**

In electric bus applications, cycle counting and C-rate management are critical parameters affecting battery degradation, warranty compliance, and total cost of ownership. Since urban buses typically operate under partial SoC windows with variable loads, equivalent cycle counting provides a more realistic assessment of battery aging compared to simple full-cycle counting methods.

Careful optimization of operating SoC range, charging strategy, and C-rate can extend battery life and improve operational efficiency.

## V. MECHANICAL RELIABILITY AND FAILURE ANALYSIS

**Mechanical Failures in Electric Buses**

Electric buses (E-buses) are increasingly deployed in urban transportation systems due to their environmental and operational advantages. However, despite having fewer moving parts than internal combustion engine (ICE) buses, E-buses are still susceptible to mechanical failures. These failures can affect reliability, safety, operational uptime, and total cost of ownership.

Mechanical failures in electric buses differ from conventional buses because of the additional weight of battery packs, regenerative braking systems, and electric drivetrains.

Major Mechanical Failure Components in E-Buses
Suspension System Failures E-buses are significantly heavier due to large lithium-ion battery packs

mounted on the roof or chassis. This increased weight causes: [4]

- Premature wear of suspension components
- Air suspension leakage
- Leaf spring fatigue (in some models)
- Shock absorber failure

Excessive loading can reduce suspension lifespan compared to diesel buses.

**Brake System Failures**

Although E-buses use regenerative braking, the mechanical brake system remains essential.
Common issues include:

- Uneven brake pad wear
- Brake disc corrosion (due to reduced mechanical braking use)
- Air compressor malfunction
- ABS sensor failure
- Regenerative braking reduces brake wear but may cause corrosion due to less frequent use of friction brakes.

**Axle and Drivetrain Issues**

**Electric buses use electric motors either:**

- Centrally mounted (connected via prop shaft), or
- Integrated e-axle systems
- Common mechanical failures:
- Differential gear wear
- Bearing failure
- Axle shaft misalignment
- Propeller shaft vibration

High torque delivery from electric motors can accelerate drivetrain component fatigue.

**Steering System Failures**

**Steering systems in E-buses may experience:**

- Hydraulic leakage (in hydraulic steering systems)
- Electric power steering motor faults
- Tie-rod end wear
- Steering rack misalignment
- Heavier front axle loads due to battery placement may increase stress on steering components.

Cooling System Mechanical Failures[3]
E-buses require cooling for:

- Battery pack
- Power electronics
- Electric motor
- Mechanical issues include:
- Coolant pump failure
- Radiator blockage
- Hose leakage
- Thermal management valve malfunction
- Cooling failure can indirectly cause battery degradation and system shutdown.

**Chassis and Structural Fatigue**

**Roof-mounted battery packs increase centre of gravity. Over time, this can result in:**

- Chassis frame cracks
- Body vibration issues
- Mounting bracket failures
- Roof structure fatigue
- Poor road conditions further accelerate structural wear.

**Tire and Wheel Failures**

**Due to higher curb weight and instant torque:**

- Faster tire wear
- Sidewall damage
- Wheel rim cracks
- Wheel alignment issues
- Improper tire pressure increases rolling resistance and energy consumption.

**Comparison with Diesel Bus Mechanical Failures**

| Component | Diesel Bus | Electric Bus |
|---|---|---|
| Engine | High failure risk | Not applicable |
| Transmission | Frequent | Minimal (single-speed) |
| Suspension | Moderate | Higher (due to weight) |

| | | |
|---|---|---|
| Brakes | High wear | Lower wear (regen braking) |
| Cooling | Engine-focused | Battery & electronics focused |

E-buses eliminate engine and gearbox failures but introduce new stress factors due to battery mass and electric torque characteristics.

**Causes of Mechanical Failures**

**Major contributing factors include:**

- Overloading beyond GVW limits
- Poor road conditions
- Improper preventive maintenance
- High C-rate acceleration patterns
- Inadequate driver training
- Thermal stress from extreme climate

**Preventive Measures**

**To reduce mechanical failure in E-buses:**

- Regular suspension inspection
- Brake system periodic activation testing
- Torque monitoring of axle components
- Scheduled coolant system checks
- Proper weight distribution design
- Predictive maintenance using telematics

Oil & Grease names and their types used in an Electric Bus (E-Bus)

| Oils Used in Electric Bus | | | |
|---|---|---|---|
| System / Component | Oil Name | Type / Grade | Purpose |
| E-Axle / Reduction Gear | Gear Oil | SAE 75W-90 / 80W-90 (GL-4 / GL-5) | Lubricates gears & bearings |
| Differential | Hypoid Gear Oil | SAE 75W-90 / 85W-140 | Reduces gear wear |
| Brake System | Brake Fluid | DOT 3 / DOT 4 | Transfers braking force |
| Power Steering (if hydraulic) | Power Steering Fluid | ATF / Hydraulic Oil ISO VG 32–46 | Smooth steering operation |
| Air Compressor | Compressor Oil | ISO VG 68 / 100 | Lubricates air brake compressor |
| Cooling System | Coolant | Ethylene Glycol Based AOT | Battery & motor cooling |
| HVAC Compressor | PAG Oil | PAG 46 / PAG 100 | Electric AC compressor lubrication |

| Grease Used in Electric Bus | |
|---|---|
| Component | Grease Type |
| Wheel Bearings | Lithium-based grease (NLGI 2) |
| Suspension Joints | Multipurpose grease |

| | |
|---|---|
| Steering Joints | EP (Extreme Pressure) grease |
| Universal Joint | Lithium complex grease |

Preventive Maintenance Work for Electric Buses (E-Bus)

Preventive maintenance (PM) of electric buses is essential to ensure operational reliability, battery longevity, passenger safety, and reduced downtime. Although electric buses eliminate engine-related maintenance, they require structured inspection and servicing of battery systems, electrical components, suspension, braking, and thermal management systems.[9]

**Preventive maintenance helps:**
- Reduce unexpected breakdowns
- Extend battery life
- Improve fleet availability
- Lower total cost of ownership

**Daily Preventive Maintenance (Pre-Trip Inspection)**
Performed by driver or depot technician before operation.

**Visual Inspection**
- Check for coolant leakage
- Inspect tire condition and air pressure
- Inspect underbody for oil/gear leaks
- Check charging port condition

**Battery & Electrical**
- Check State of Charge (SoC)
- Verify no warning lights on dashboard
- Inspect high-voltage cable insulation

**Brake & Steering**
- Check brake air pressure
- Test service brake and parking brake
- Check steering free play

**Weekly Preventive Maintenance**
- Clean battery cooling filters
- Check coolant level
- Inspect air compressor
- Lubricate suspension grease points
- Inspect door mechanism
- Inspect roof-mounted battery mounts

**Monthly Preventive Maintenance**
**Battery System**
- Check battery temperature logs
- Inspect BMS fault codes
- Verify insulation resistance

**Drivetrain**
- Check gear oil level in e-axle
- Inspect axle bolts torque
- Check motor mounting bolts

**Suspension & Steering**
- Inspect air suspension bags
- Check shock absorbers
- Inspect tie rods and steering joints

**Quarterly / 10,000–20,000 km Maintenance**
- Replace cabin air filter
- Inspect brake pads & discs
- Drain moisture from air tanks
- Check wheel alignment
- Check differential gear oil condition
- Inspect cooling system pump operation

**Annual Maintenance**
**Battery**
- Capacity test
- Internal resistance check
- Thermal system flushing

**Mechanical**
- Replace gear oil
- Replace brake fluid (if required)
- Replace compressor oil

- Suspension overhaul if required

## VI. SEASON-WISE PERFORMANCE EVALUATION (INDIAN CONDITIONS)

▪ Season-Wise Maintenance, Preventive Plan & Common Failures Guide for Electric Buses (India Conditions) — especially useful for city operations (7m / 9m / 12m e-bus fleets).

**Standards referred:**

- Automotive Industry Standards (AIS 153 – electric bus safety)
- Ministry of Road Transport and Highways (CMVR compliance)
- Bureau of Indian Standards (electrical & material standards)

India has 3 major operating seasons affecting E-bus performance:

- ☀ Summer (March–June)
- 🌧 Monsoon (July–September)
- ❄ Winter (October–February)

**SUMMER SEASON (High Temperature 35–48°C)**
**Common Failures in Summer**

- Battery overheating / thermal derating
- HVAC overload (AC trip)
- Motor controller overheating
- DC-DC converter failure
- Reduced range (5–15% drop)
- Tyre burst (road heat effect)
- Preventive Maintenance Plan

**Battery System**

- Check coolant level weekly
- Inspect battery cooling pump
- Clean radiator fins
- Check insulation resistance
- Verify BMS temperature logs daily
- Ensure battery compartment ventilation

**If battery temperature > 45°C → derating starts.**
**Power Electronics**

- Clean inverter cooling fans
- Tighten HV cable terminals
- Scan fault codes (weekly)

**HVAC**

- Clean AC condenser every 15 days
- Check refrigerant pressure
- Inspect compressor load current
- Tyres
- Maintain correct air pressure
- Avoid overloading (affects heating)

**MONSOON SEASON (High Humidity + Water)**
**Common Failures**

- Water ingress in battery compartment
- HV cable short circuit
- ABS sensor malfunction
- Door pneumatic failure
- Rusting of body structure
- Air brake moisture problems

**Preventive Maintenance Plan**
**Battery & HV System**

- Inspect IP67 sealing
- Check rubber gaskets
- Perform insulation resistance test
- Apply dielectric grease on connectors
- Ensure drain holes are clear

**Electrical System**

- Check earthing continuity
- Inspect junction boxes
- Clean relay panels
- Braking System
- Drain air tank daily
- Check moisture separator
- Inspect ABS wiring
- Body & Structure
- Anti-rust coating inspection
- Check underbody paint
- Tighten structural bolts

**WINTER SEASON (Low Temp 5–15°C)**
**Common Failures**

- Battery capacity reduction (10–20%)
- Slow charging
- Low air pressure build-up
- Door operation delay
- Suspension stiffness
- Preventive Maintenance Plan
- Battery
- Pre-heating system check
- Monitor SOC calibration
- Avoid deep discharge
- Slow overnight charging preferred
- Pneumatic System

- Check air dryer
- Inspect compressor performance
- Drain air tank daily
- Charging
- Inspect charging connector pins
- Clean CCS2 port
- Avoid charging in heavy fog without protection

## VII. PREVENTIVE MAINTENANCE AND FLEET MANAGEMENT

**Recommended Maintenance Schedule [9,10,11]**
**Daily Checks (Driver Level)**

- SOC level
- Warning lights
- Brake air pressure
- Door operation
- AC working
- Tyre condition
- 🔹 Weekly Checks
- Battery coolant level
- Fault code scan
- HV cable inspection
- Air tank draining
- Suspension air leak check
- 🔹 Monthly Checks
- Insulation resistance test
- Brake lining wear
- Steering linkage inspection
- BMS data analysis
- Thermal imaging of battery
- 🔹 Quarterly
- Complete electrical diagnostic
- Battery capacity test
- Motor bearing inspection
- Structural bolt torque check

Major Failure Categories in E-Bus

| System | % Failure Contribution |
|---|---|
| HVAC | 25–30% |
| Battery & BMS | 20–25% |

Season-Wise Maintenance, Preventive Plan & Common Failures Guide for Electric Buses (India Conditions) — specially useful for city operations (7m / 9m / 12m e-bus fleets).

**Standards referred:**

- Automotive Industry Standards (AIS 153 – electric bus safety)
- Ministry of Road Transport and Highways (CMVR compliance)
- Bureau of Indian Standards (electrical & material standards)
- India has 3 major operating seasons affecting E-bus performance:

Summer (March–June)
Monsoon (July–September)
Winter (October–February)

EV bus fault codes are categorized by the system they impact: P (Powertrain/Battery), U (Network/Communication), C (Chassis), and B (Body).

Powertrain & Battery (P-Codes)
These codes are the most critical for EV bus operation and safety.[7]

| Code | Meaning | Diagnosis | Rectification |
|---|---|---|---|
| P0A80 | Replace HV Battery Pack | Battery capacity or voltage has dropped below safe thresholds. | Perform battery balancing using a Grid Charger or replace degraded modules. |
| P0A0D | HV System Interlock Open | A safety loop (HVIL) is broken, often due to a loose connector. | Check all HV orange cable connections and interlock pins for continuity. |

| | | | |
|---|---|---|---|
| P1A10 | Battery Cooling Fault | Coolant pump failure or fan malfunction. | Inspect the coolant pump, radiator, and fan harness for blocks or electrical opens. |
| P0C73 | Motor Position Sensor | Malfunction in the sensor that tells the controller the motor's position. | Check the sensor wiring and calibrate the motor controller using a diagnostic tool. |
| P0AFA | Battery Voltage Too High | Charger issue or stuck high-voltage contactor. | Test contactor operation; if stuck, replace the HV Contactor. |

Network & Communication (U-Codes)[11]

Communication errors often prevent the bus from starting.

| Code | Meaning | Diagnosis | Rectification |
|---|---|---|---|
| U0100 | Lost Comm with ECM/PCM | Main controller is not "talking" to the rest of the bus. | Check the 12V/24V power supply to the ECM and verify CAN Bus resistance (should be 60 ohms). |
| U0111 | Lost Comm with BMS | Loss of communication with the Battery Management System. | Inspect the CAN High/Low wiring between the BMS and the central VCU. |
| U0110 | Lost Comm with Motor Module | The drive motor controller is offline. | Ensure the controller is receiving its wake-up signal and check the communication harness. |

Charging & Chassis (C-Codes)

| Code | Meaning | Diagnosis | Rectification |
|---|---|---|---|
| C1241 | Low Battery Positive Voltage | 12V/24V auxiliary battery is weak. | Test the DC-DC converter output; recharge or replace the auxiliary battery. |
| 00400A | Emergency Button Pressed | Software detects the e-stop is active. | Physically release the Emergency Button on the dash or near the charger port. |

**Common ABS Fault Codes** Buses typically use WABCO or ZF/Meritor ABS systems, which use specific "Blink Codes" or standard OBD "C" (Chassis) codes.

| Code | Component | Problem | Possible Cause |
|---|---|---|---|
| C0035 / 31 | Front Wheel Sensor | No signal or erratic speed data. | Air gap too large, dirty tone ring, or broken wire. |
| C0045 / 43 | Rear Wheel Sensor | Open circuit or signal implausible. | Sensor has moved away from the Rotor/Tone Ring. |
| C0110 / 71 | ABS Pump Motor | Pump motor not responding. | Blown fuse, stuck relay, or internal Pump Motor Failure. |
| C1226 / 41 | Solenoid Valve | Inlet/Outlet valve circuit fault. | Corroded connector or faulty ABS Solenoid Valve. |
| U0121 | ABS Module | Lost communication with ABS unit. | Wiring harness issue or ABS Control Module needs programming. |

## VIII. DRIVER TRAINING AND HUMAN FACTORS

### Driver Training and Support for Electric Bus (E-Bus) Operations

Driver training is a critical component in the successful deployment of electric buses. Unlike conventional diesel buses, electric buses require drivers to understand battery behaviour, regenerative braking, high-voltage safety awareness, and energy-efficient driving techniques. Proper driver training improves vehicle range, reduces battery degradation, enhances passenger safety, and lowers operational costs.[8]

### Objectives of E-Bus Driver Training

The primary objectives of electric bus driver training include:[8]

- Safe handling of high-voltage vehicles
- Efficient energy management
- Maximizing driving range
- Minimizing mechanical and battery stress
- Improving passenger comfort
- Understanding emergency procedures

### Core Training Modules

**Introduction to Electric Bus Technology**

- Basic components: battery pack, electric motor, inverter, BMS
- Differences between diesel and electric buses
- Understanding dashboard indicators

### Energy-Efficient Driving Techniques

Efficient driving significantly affects battery life and vehicle range.[8]

**Key practices:**

- Smooth acceleration and deceleration
- Avoiding harsh braking
- Optimizing regenerative braking usage
- Maintaining steady speeds
- Avoiding unnecessary idling (HVAC load management)
- Eco-driving can improve energy efficiency by 5–15%.

### Battery Awareness Training [7][8]

**Drivers should understand:**

- State of Charge (SoC)
- State of Health (SoH) (basic awareness)
- Impact of deep discharge on battery life
- Charging schedules and depot protocols
- Avoiding very low SoC levels reduces long-term battery degradation.

### Regenerative Braking Training

Regenerative braking converts kinetic energy into electrical energy.

**Training includes:**
- Proper pedal control
- Anticipatory driving
- Maximizing energy recovery in city routes
- Safe downhill driving

**High-Voltage Safety Awareness**

Drivers are not required to repair HV systems, but they must:
- Recognize HV warning symbols
- Avoid touching orange HV cables
- Report electrical faults immediately
- Follow emergency isolation procedures

**Emergency Response Training**

**Drivers must be trained for:**
- Battery fire incidents
- Electrical faults
- Vehicle breakdown
- Passenger evacuation
- First aid procedures

**Simulator and Practical Training**

**Modern driver training programs include:**
- Driving simulators for eco-driving practice
- Real-world route testing
- Range prediction exercises
- Charging operation demonstration

Practical training improves confidence and reduces operational errors.

**Continuous Driver Support System**

**Effective driver support includes:**

**Telematics Monitoring**
- Real-time energy consumption tracking
- Driving behaviour analysis
- Harsh acceleration alerts

**Feedback Mechanism**
- Monthly performance reports
- Energy efficiency scorecards

Incentive-based performance systems

**Technical Helpdesk**
- 24/7 control room support
- Remote diagnostics assistance
- Fault troubleshooting guidance

**Benefits of Proper Driver Training**

| Aspect | Impact |
|---|---|
| Battery Life | Increased |
| Range Efficiency | Improved |
| Maintenance Cost | Reduced |
| Passenger Comfort | Enhanced |
| Breakdown Incidents | Decreased |

Studies indicate that trained drivers can improve energy efficiency by up to 10–20% compared to untrained operators.[8]

**Challenges in Driver Training**
- Resistance to technology change
- Limited EV technical knowledge
- Anxiety about battery range
- Lack of standardized national curriculum

Structured training programs help overcome these challenges.

Driver training and support are essential for optimizing electric bus performance and ensuring safe operations. A well-designed training program, combined with telematics-based monitoring and continuous support, enhances operational efficiency, reduces energy consumption, and extends battery lifespan. Human factors remain a key determinant of electric bus fleet success.[8]

**Techno-Economic and Analysis E-Bus**

E-Bus Policies

India has implemented several policies to accelerate the adoption of e-buses: [5]
- FAME India Scheme: The Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) scheme is a flagship policy providing subsidies for electric vehicles, including e-buses,

and supporting the development of charging infrastructure.

- National Electric Mobility Mission Plan 2020 (NEMMP 2020): While not explicitly detailed in the provided documents, this broader plan aimed to promote hybrid and electric vehicle technology, setting the stage for subsequent e-bus initiatives.
- Emissions Reduction Targets: The Indian government has set ambitious targets for electric vehicle fleets by 2030 to mitigate the environmental impact of rapid urbanization and commuter traffic. This target acts as a strong policy directive for e-bus adoption.
- Public-Private Partnerships (PPPs): Policies are increasingly encouraging PPP models to address the substantial financing challenges associated with large-scale e-bus programs. These partnerships are crucial for accelerating deployment and building a sustainable public transport ecosystem.
- State-level Initiatives: Beyond national policies, individual states and cities are developing their own frameworks and incentives to promote e-bus integration into their public transport systems.

**Types of E-Buses**

- The provided sources do not delve into specific technical classifications or "types" of e-buses in detail. However, based on the context of public transportation electrification, general categories can be inferred:

Battery Electric Buses (BEBs): These are the most common type, relying solely on electric batteries for propulsion and requiring charging infrastructure [7]. Their range and charging times are critical operational considerations.

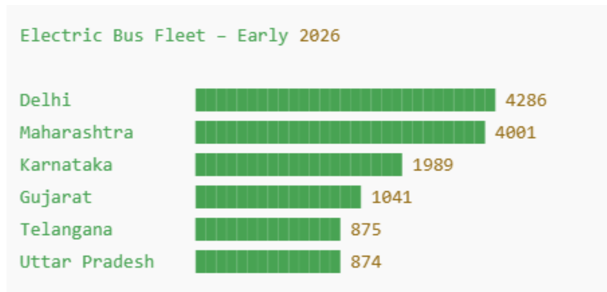
Opportunity Charging Buses: These e-buses are designed for frequent, rapid charging at stops or termini, maximizing operational uptime.

Overnight Charging Buses: These buses have larger battery capacities and are charged primarily overnight at depots.

Hybrid Electric Buses: While the primary focus of the discussed policies is on zero-emission battery electric vehicles, hybrid electric buses (which combine internal combustion engines with electric motors) could serve as an intermediate step, though the emphasis is clearly shifting towards pure electric solutions for achieving carbon neutrality.

The deployment of these e-bus types depends on various factors such as route length, passenger capacity requirements, and the availability of suitable charging infrastructure. The overall shift towards e-mobility is considered a crucial step for India to achieve environmental sustainability, improve public health, and enhance energy independence

Top state of E-bus adoptions




**Highlights & National Context**

Leading States by Fleet Size

- Delhi largest total EV bus fleet, with expansions into intercity electric services.
- Maharashtra substantial fleets in multiple cities.
- Karnataka strong urban adoption and central allocations.
- Uttar Pradesh, Gujarat, and Odisha also among higher adopters

**City vs Intercity Operations**

- City/Intracity: Most states run EV buses primarily within cities or urban agglomerations (e.g., Delhi, Mumbai, Hyderabad, Bengaluru).
- Intercity Electric Services: Some regions have started intercity EV bus operations (e.g., Delhi to Panipat/Dharuhera), but these are early stages and not yet uniform nationwide.

**Government Programs Boosting Adoption**

- National Electric Bus Programme (NEBP) — aims to deploy tens of thousands of e-buses across India.
- PM e-Bus Sewa / PM e-Drive Schemes — central tenders allocating large numbers of e-buses for city/state operations

**Chargers for Electric Buses**

Electric buses (e-buses) use various charging technologies to recharge their batteries, depending on factors like battery capacity, operational needs, and infrastructure. Common types include:

- Depot Charging (Slow Charging): Typically, AC-based (e.g., 22-150 kW), done overnight at bus depots. It uses standard plugs or pantographs and is cost-effective for full recharge but requires long downtime (4-8 hours).
- Opportunity Charging (Fast Charging): DC-based (e.g., 150-450 kW), installed at bus stops or terminals for quick top-ups (10-30 minutes). This supports longer routes without large battery packs.
- Ultra-Fast Charging: DC-based (up to 1 MW or more), used for rapid charging in minutes. Often employs pantograph systems for overhead connection.
- Wireless Charging: Inductive charging via pads on the road or at stops, reducing wear on connectors. Still emerging but used in pilot projects.
- Pantograph Charging: Overhead robotic arms that connect to the bus roof for automated charging, common in Europe and Asia for depot or en-route use

## IX. CONCLUSION

This study presented a comprehensive multi-scale evaluation of electric bus systems operating under Indian climatic and duty-cycle conditions, integrating battery degradation modelling, mechanical reliability assessment, seasonal performance analysis, and techno-economic evaluation. The findings confirm that environmental stressors, high operational loads, and aggressive charging practices significantly influence long-term system reliability and lifecycle cost.

Battery degradation analysis revealed that elevated ambient temperatures above 35°C, high C-rate charging, and deeper depth of discharge cycles accelerate capacity fade and internal resistance growth in both LFP and NMC chemistries. Thermal stress emerged as a dominant degradation driver, particularly under summer operating conditions typical of many Indian cities. The developed predictive State of Health (SoH) framework demonstrated the importance of adaptive charging strategies and controlled duty-cycle management to extend battery service life.

Mechanical reliability assessment using FMEA and structural stress analysis showed that additional mass from battery integration increases suspension loading, axle stress, and chassis fatigue risk compared to conventional diesel buses. Seasonal factors further influence performance, with summer-induced thermal derating, monsoon-related electrical ingress risks, and winter capacity reduction affecting operational consistency and reliability.

The techno-economic analysis indicates that although electric buses involve higher upfront capital expenditure, lifecycle optimization through predictive maintenance, telematics-based diagnostics, optimized charging protocols, and driver training substantially improves total cost of ownership. When degradation-aware operational strategies are implemented, long-term economic viability becomes comparable or favorable relative to conventional fleets.

Overall, this research establishes a predictive reliability and lifecycle optimization framework tailored to Indian operating environments. The results provide actionable guidance for policymakers, fleet operators, and manufacturers to enhance battery longevity, improve mechanical durability, reduce operational risks, and accelerate the sustainable electrification of public transportation in India.

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