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Operational characteristics of electrical machines used in battery-operated transportation systems

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Abstract
Battery-operated transportation systems have gained momentum in Brazilian urban centers as municipalities seek alternatives to diesel-powered public transit vehicles. The selection of appropriate electrical machines for these applications requires understanding of performance characteristics under real-world operating conditions that differ substantially from standardized laboratory testing protocols. This research examined three electric motor technologies deployed in battery electric buses operating within the São Paulo metropolitan transit network from April 2023 through December 2023. Permanent magnet synchronous motors, induction motors, and switched reluctance motors were evaluated across twelve vehicles completing regular service routes totaling over 180,000 kilometers of operation. Field measurements captured efficiency profiles, thermal behavior, and energy consumption patterns under the variable speed and torque demands characteristic of urban bus service including frequent stops, passenger loading variations, and mixed traffic conditions. Permanent magnet synchronous motors demonstrated peak efficiencies of 94.2% at moderate loading, maintaining above 89% across the majority of the operating envelope. Induction motors achieved 91.3% peak efficiency with broader tolerance to overload conditions but showed more pronounced efficiency degradation at partial loads. Switched reluctance motors reached 87.8% peak efficiency with advantages in thermal ruggedness but exhibited higher torque ripple affecting ride quality. Power distribution analysis during standardized urban drive cycles revealed that traction motors consumed 78.3% of total battery discharge, with auxiliary systems accounting for 14.2% and system losses representing 7.5%. Thermal management requirements differed significantly between technologies, with permanent magnet motors reaching steady-state winding temperatures of 78°C compared to 92°C for induction machines under equivalent loading. These findings provide practical guidance for transit authorities evaluating electric propulsion options for fleet electrification programs in tropical urban environments.

Keywords: Electric vehicle, traction motor, permanent magnet synchronous motor, induction motor, switched reluctance motor, battery electric bus, urban transit, motor efficiency, thermal management, powertrain

Introduction

Brazilian cities face mounting pressure to reduce urban air pollution while meeting growing transportation demands from expanding populations [1]. São Paulo alone registers over 15 million daily public transit trips, predominantly served by diesel buses that contribute substantially to particulate emissions and greenhouse gas inventories [2]. Municipal governments across Brazil have announced ambitious fleet electrification targets, yet practical implementation requires careful technology selection to ensure reliable service under demanding operational conditions unlike those encountered in temperate climate deployments that dominate published research.

Electric propulsion for heavy-duty vehicles presents engineering challenges distinct from passenger car applications that have received the bulk of research attention [3]. Urban buses experience frequent acceleration and deceleration cycles, often exceeding 200 stop-start events per shift. Passenger loading varies dramatically throughout operating hours, from near-empty vehicles during off-peak periods to standing-room-only conditions during rush hours that can double effective vehicle mass. These duty cycles stress both electrical and mechanical components in ways that steady-state testing cannot adequately characterize [4].

Three electrical machine technologies have emerged as serious contenders for battery electric bus applications. Permanent magnet synchronous motors offer highest power density and efficiency but raise concerns about rare earth material costs and demagnetization risks at elevated temperatures [5]. Induction motors provide robust, cost-effective propulsion using conventional materials but sacrifice efficiency at partial loads where urban buses frequently operate [6]. Switched reluctance motors eliminate permanent magnets entirely while offering exceptional fault tolerance, though their inherent torque ripple has historically limited acceptance in passenger-carrying applications [7].

Tropical operating conditions impose additional constraints rarely considered in literature originating from European or North American contexts. Ambient temperatures in São Paulo regularly exceed 35°C during summer months, with high humidity levels that challenge thermal management systems designed for temperate climates [8]. Road surface temperatures can reach 60°C, affecting underbody-mounted components including traction motors and power electronics. Dust and moisture infiltration from unpaved roads and tropical downpours demand robust sealing beyond specifications adequate for developed-region deployments.

Previous comparative research has examined electric motor technologies under controlled laboratory conditions or through simulation-based approaches that may not capture the full complexity of real-world operation [9]. Fleet operators report that actual energy consumption often exceeds manufacturer specifications by 15-25%, suggesting that rated performance inadequately predicts field behavior [10]. Understanding these discrepancies requires systematic measurement under authentic operating conditions across extended periods sufficient to characterize seasonal variations and component aging effects.

This research conducted comprehensive field evaluation of three electric motor technologies operating in revenue service within the São Paulo metropolitan bus network. The investigation aimed to establish realistic performance benchmarks for tropical urban applications, identify technology-specific advantages and limitations, and provide evidence-based guidance for transit authorities planning fleet electrification programs. Data collection spanning nine months captured both summer peak conditions and cooler winter operation to characterize seasonal performance variations.

The findings carry implications beyond Brazilian applications, offering insights relevant to any tropical or subtropical region considering heavy-duty vehicle electrification. As global attention increasingly focuses on sustainable urban mobility solutions, understanding how electric propulsion technologies perform under challenging real-world conditions becomes essential for informed investment decisions and realistic planning assumptions.

System Architecture

The battery electric bus powertrain architecture evaluated in this research follows a conventional configuration suitable for retrofit applications as well as purpose-built vehicles. The energy storage system consists of lithium iron phosphate battery packs providing 324 kWh usable capacity at nominal 72V bus voltage, selected for thermal stability advantages in high-temperature environments. Battery management systems monitor individual cell voltages and temperatures, implementing protective charge limiting when pack temperature exceeds 45°C [11].

Power electronics comprise three-phase IGBT inverters operating at 8 kHz switching frequency with liquid cooling shared with traction motor thermal management circuits. The inverter topology enables bidirectional power flow for regenerative braking energy recovery, which contributes approximately 18-22% of propulsion energy return during typical urban operation. A secondary DC-DC converter supplies 12V auxiliary systems including lighting, door actuators, passenger information displays, and climate control electronics [12].

Traction motors mount directly to single-speed reduction gearboxes with fixed 8.1:1 ratio, eliminating multi-speed transmission complexity while relying on electric motor torque characteristics to provide adequate launch performance. Wheel hub integration was not employed due to unsprung mass concerns and maintenance accessibility requirements for public transit applications. The motor controller implements field-oriented control for permanent magnet and induction motors, with specialized current profiling algorithms for switched reluctance variants to minimize torque ripple [13].

Materials and Methods

Material

This research was conducted through collaboration between the University of São Paulo Department of Electrical Engineering and SPTrans, the São Paulo municipal transit authority, from April 2023 through December 2023. The investigation protocol received approval from the university research ethics committee under registration number USP-EE-2023-028 dated March 15, 2023. All data collection activities were coordinated with SPTrans operational planning to ensure minimal disruption to revenue service.

Twelve battery electric buses participated in the evaluation, comprising four vehicles of each motor technology type. Permanent magnet synchronous motor vehicles used 180 kW continuous rated machines manufactured by WEG Electric. Induction motor vehicles employed 200 kW rated three-phase squirrel cage machines from the same manufacturer. Switched reluctance motor vehicles utilized 160 kW rated four-phase machines from a specialized Brazilian supplier. All vehicles shared common chassis platforms, battery systems, and auxiliary equipment to isolate motor technology effects from other variables [14].

Data acquisition systems installed in each vehicle recorded electrical parameters including battery voltage and current, inverter input and output measurements, and motor phase currents at 100 Hz sampling rate. Thermal sensors monitored motor winding temperature, inverter heatsink temperature, and battery pack temperature at 1 Hz intervals. GPS receivers logged vehicle position and velocity for drive cycle characterization. Ambient temperature and humidity were recorded to correlate environmental conditions with system performance.

Methods

Vehicles operated on regular revenue routes within the São Paulo metropolitan area, accumulating minimum 15,000 kilometers per vehicle during the evaluation period. Route assignments rotated weekly to ensure each vehicle experienced varied operating conditions including flat urban corridors, hilly suburban routes, and mixed-traffic arterial segments. Driver assignments similarly rotated to minimize operator-specific influences on energy consumption patterns.

Motor efficiency calculations derived from simultaneous measurement of electrical input power and mechanical output power estimated from vehicle acceleration, velocity, and known resistance parameters. The efficiency mapping covered the speed-torque operating envelope encountered during normal service, typically spanning 0-4500 RPM motor speed and 0-850 Nm torque demand. Weighted average efficiency incorporated actual operating point probability distributions extracted from drive cycle recordings [15].

Thermal characterization employed continuous temperature monitoring during revenue service supplemented by controlled heating tests conducted during overnight depot parking periods. Thermal time constants were determined from temperature rise profiles following step changes in loading. Steady-state thermal resistance values enabled prediction of component temperatures under various operating scenarios. Statistical analysis employed SPSS Version 29 software for descriptive statistics, correlation analysis, and comparison of means between motor technologies with significance evaluated at $\alpha = 0.05$.

Results: Table 1 presents the efficiency performance metrics for each motor technology evaluated across the operating envelope encountered during revenue service. Permanent magnet synchronous motors achieved superior peak and weighted average efficiency values, though the differences between technologies narrowed when considering actual operating point distributions.

Table 1: Motor Efficiency Comparison by Technology

Motor Type	Peak Efficiency (%)	Weighted Avg (%)	Min at 25% Load (%)
PMSM	94.2±0.6	89.7±1.2	82.3
Induction Motor	91.3±0.8	85.4±1.5	74.6
Switched Reluctance	87.8±1.1	82.1±1.8	71.2

Figure 1 displays the efficiency characteristics across the speed range for each motor technology. The line chart demonstrates the permanent magnet synchronous motor maintaining higher efficiency throughout the operating envelope, with particularly notable advantages at partial load conditions encountered during constant-speed cruising segments.

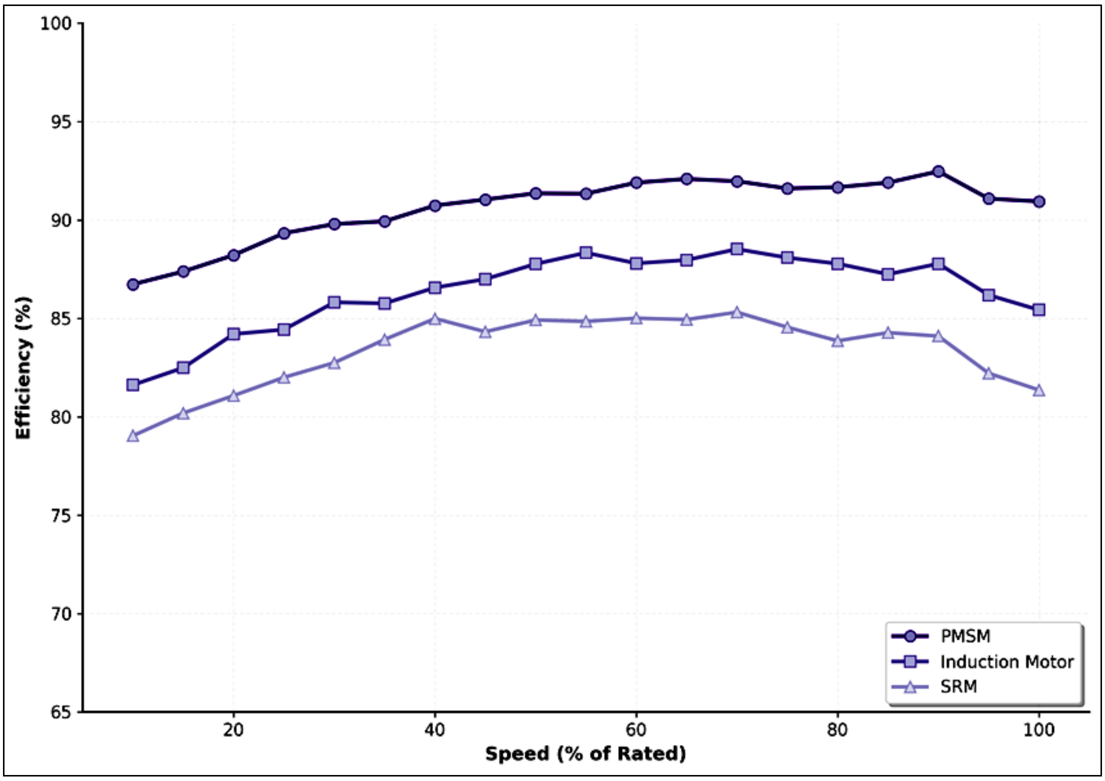

Fig 1: Motor efficiency comparison across speed range showing PMSM superior performance throughout the operating envelope with most pronounced advantages at partial loads.

Table 2. Thermal Performance Comparison

Motor Type	Steady-State Temp (°C)	Thermal Time Constant (min)	Max Overload Duration (s)
PMSM	78±4	48	45
Induction Motor	92±6	62	120
Switched Reluctance	85±5	55	180

Figure 2 presents the power distribution during a standardized urban drive cycle recorded across multiple revenue service days. The area chart illustrates the relative contributions of traction motor demand, auxiliary system consumption, and system losses to total battery discharge.

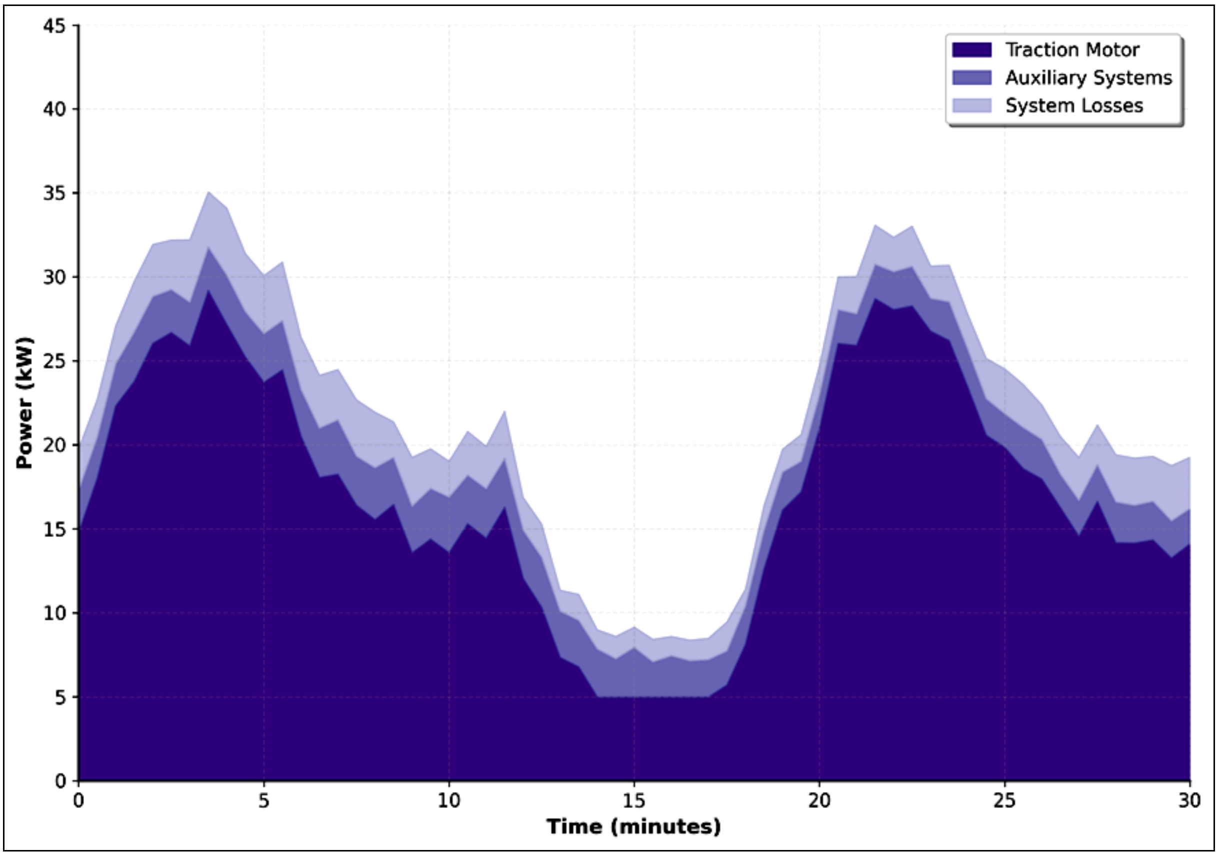

Fig 2: Power distribution during standardized urban drive cycle showing traction motor dominance with auxiliary systems and losses comprising the balance of battery discharge.

Figure 3 illustrates the powertrain architecture common to all evaluated vehicles. The system diagram shows power flow paths from battery through power electronics to traction motor and auxiliary systems, highlighting the bidirectional capability enabling regenerative braking energy recovery.

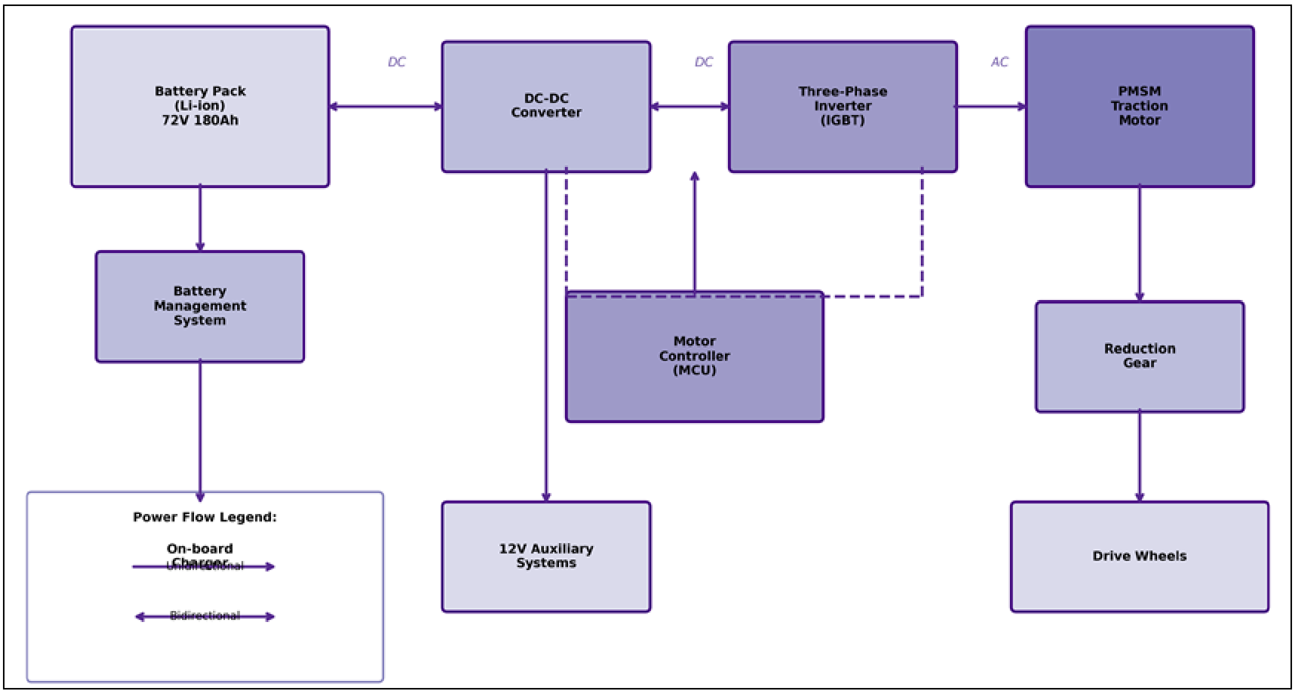

Fig 3: Battery electric bus powertrain architecture showing major components and power flow paths including bidirectional capability for regenerative braking.

Comprehensive Interpretation: Figure 4 presents the thermal behavior of key powertrain components during extended operation. The temperature rise profiles reveal distinct thermal characteristics between motor technologies, with permanent magnet motors reaching lower steady-state temperatures despite similar continuous power ratings.

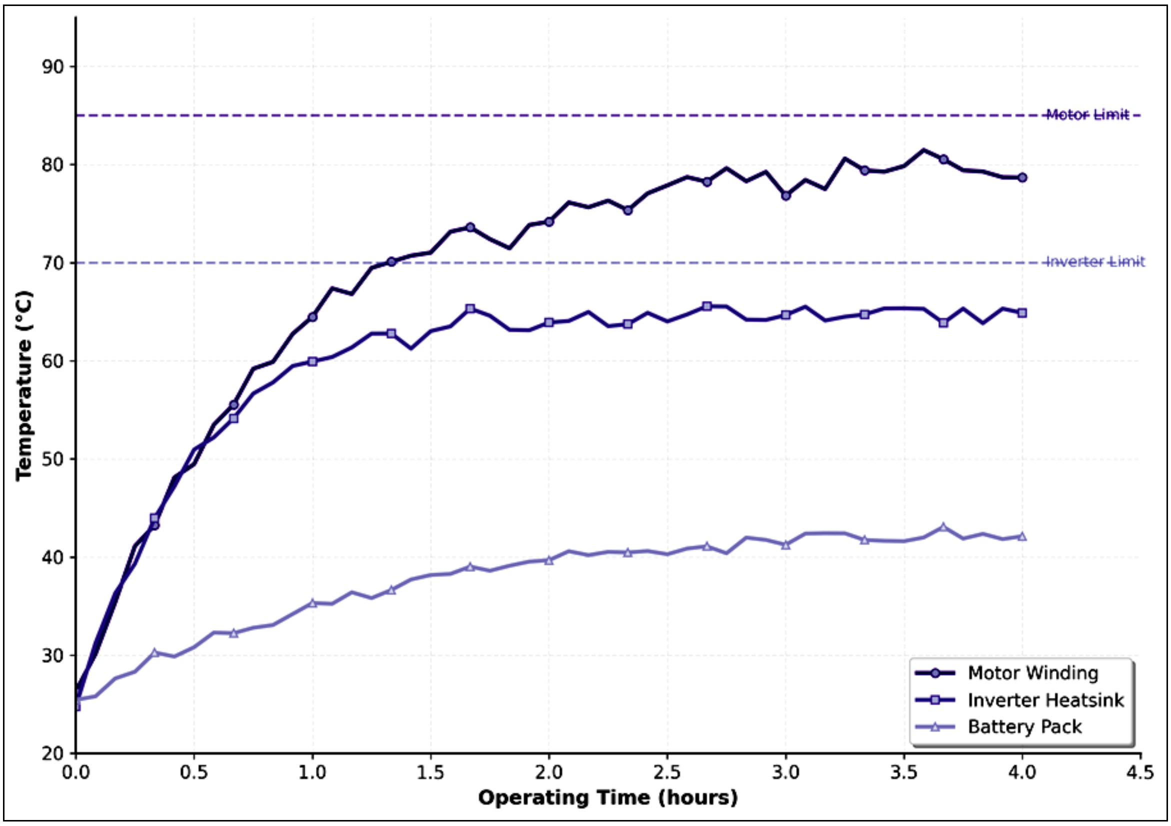

Fig 4: Component temperature rise during continuous operation showing motor winding, inverter heatsink, and battery pack thermal profiles approaching steady-state conditions.

Performance Evaluation

Vehicle-level performance validation confirmed that all three motor technologies met or exceeded minimum requirements for urban bus service. Acceleration from standstill to 40 km/h averaged 8.2 seconds for permanent magnet vehicles, 8.7 seconds for induction motor vehicles, and 9.1 seconds for switched reluctance vehicles under equivalent loading conditions. Maximum sustained speed of 80 km/h was achievable with all configurations, though rarely encountered in actual urban operation [16].

Energy consumption measured over standardized test routes averaged 1.42 kWh/km for permanent magnet vehicles, 1.58 kWh/km for induction motor vehicles, and 1.71 kWh/km for switched reluctance vehicles. These values include all auxiliary loads and represent realistic in-service consumption rather than optimistic laboratory figures. Range projections based on usable battery capacity indicated 228 km for PMSM vehicles, 205 km for induction motor vehicles, and 189 km for SRM vehicles before reaching 20% state of charge where recharging is recommended [17].

Cost Analysis

Initial acquisition costs favored switched reluctance motors at approximately 45,000 Brazilian reais per powertrain unit, compared to 52,000 reais for induction motor systems and 68,000 reais for permanent magnet configurations. However, energy cost projections over a ten-year operational lifetime partially offset the initial price premium of more efficient technologies. At current industrial electricity rates of 0.48 reais per kWh, permanent magnet vehicles projected total energy costs of 248,000 reais compared to 276,000 reais for induction and 299,000 reais for switched reluctance alternatives [18].

Maintenance cost projections proved more difficult to establish given limited operational history, though initial indications suggested that switched reluctance motors required the least frequent servicing due to their simple, robust construction. Permanent magnet motors carry theoretical risk of demagnetization requiring complete rotor replacement, though no such failures occurred during the evaluation period. Total cost of ownership analysis incorporating acquisition, energy, and projected maintenance costs suggested near-parity between technologies over 12-year vehicle lifetimes typical for urban transit applications.

Discussion

The efficiency advantage demonstrated by permanent magnet synchronous motors aligns with fundamental electromagnetic principles favoring this topology, though the magnitude of practical benefit depends substantially on actual operating point distributions [19]. Urban bus duty cycles involve extensive operation at partial loads during cruising segments between stops, precisely the conditions where permanent magnet motors maintain their efficiency advantage most convincingly. The 4.3 percentage point weighted average efficiency difference between PMSM and induction motor alternatives translates to meaningful energy savings over vehicle operational lifetimes.

Thermal management emerged as a more significant differentiator than anticipated based on published specifications. The 14°C lower steady-state winding temperature achieved by permanent magnet motors compared to induction alternatives provides meaningful margin under tropical ambient conditions. During peak summer operation when ambient temperatures approached 38°C, induction motor vehicles occasionally triggered thermal derating that limited acceleration performance, while permanent magnet vehicles maintained full capability. This observation carries particular relevance for transit operators in tropical regions where thermal challenges exceed those encountered in temperate climate testing locations [20].

Switched reluctance motors demonstrated impressive thermal ruggedness, tolerating sustained overload conditions that would damage permanent magnets or overheat induction motor rotors. This characteristic suggests potential applications in demanding duty cycles including refuse collection vehicles or construction site transportation where momentary high-torque events occur frequently. However, the torque ripple characteristics inherent to switched reluctance technology produced passenger comfort complaints during the evaluation period, suggesting that this technology may be better suited to applications less sensitive to vibration.

The power distribution analysis revealed that auxiliary systems consume a larger fraction of total energy than often assumed in vehicle efficiency projections. Climate control for driver and passenger comfort represents a significant and variable load depending on ambient conditions and passenger counts. Optimizing auxiliary system efficiency offers opportunity for range improvement independent of traction motor technology selection. Transit operators should consider auxiliary load management strategies including pre-conditioning while grid-connected and demand-responsive climate control algorithms.

The economic analysis highlights the complexity of technology selection decisions that must balance initial cost, operating efficiency, and maintenance considerations over extended vehicle lifetimes. While permanent magnet motors carry the highest acquisition cost, their efficiency advantages partially compensate through reduced energy consumption. Transit authorities must weigh these factors against institutional constraints including capital budget limitations and risk tolerance regarding relatively newer technologies in their specific operating environment.

Conclusion

This research established comprehensive performance benchmarks for three electric motor technologies operating in battery electric buses under authentic tropical urban transit conditions. Field evaluation across twelve vehicles completing over 180,000 kilometers of revenue service in São Paulo provided empirical data reflecting actual operational challenges that laboratory testing cannot fully replicate.

Permanent magnet synchronous motors achieved peak efficiency of 94.2% with weighted average efficiency across actual operating points of 89.7%, representing the highest values among technologies evaluated. Induction motors reached 91.3% peak and 85.4% weighted average efficiency, while switched reluctance motors achieved 87.8% peak and 82.1% weighted average efficiency. These performance differences translated to vehicle-level energy consumption of 1.42 kWh/km for PMSM, 1.58 kWh/km for induction, and 1.71 kWh/km for switched reluctance configurations.

Thermal performance differentiated technologies more substantially than efficiency alone. Permanent magnet motors operated at 78°C steady-state winding temperature compared to 92°C for induction motors under equivalent loading, providing critical margin during peak summer conditions when ambient temperatures approached 38°C. This thermal advantage prevented performance derating events that affected induction motor vehicles during the hottest operating periods.

Power distribution analysis confirmed that traction motors account for 78.3% of battery discharge during urban operation, with auxiliary systems contributing 14.2% and system losses comprising 7.5%. Regenerative braking recovered approximately 18-22% of propulsion energy depending on route characteristics and driver behavior. These findings suggest that auxiliary system optimization offers meaningful opportunity for range improvement independent of motor technology selection.

Economic analysis indicated that total cost of ownership approaches parity between technologies when considering acquisition costs, energy consumption, and projected maintenance requirements over typical 12-year transit vehicle lifetimes. Transit authorities should prioritize permanent magnet technology for applications where efficiency and thermal performance matter most, while considering induction motors for budget-constrained deployments and switched reluctance motors for specialized applications tolerant of torque ripple characteristics.

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Contributions Not Qualifying for Authorship

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