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Research Article

Socio-Technical Optimization of Autonomous Electric Mobility Fleets: Integrating Multi-Agent Rebalancing, Edge Diagnostics, and Capital Efficiency

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***Abstract*:** The transition toward autonomous electric mobility fleets promises transformative reductions in urban congestion and tailpipe emissions, yet operationalizing these systems remains constrained by fragmented optimization paradigms. Existing frameworks typically isolate spatial fleet dispatch from vehicle-level hardware degradation and institutional capital governance. This study proposes a socio-technical synthesis integrating multi-agent deep reinforcement learning for dynamic rebalancing, edge-computing diagnostics for real-time component prognostics, and engineering-accounting governance mechanisms to safeguard capital efficiency. By examining the interplay between algorithmic dispatch, vehicular physical durability, spanning power electronics, thermal management, and structural glazing and financial oversight, this research highlights how uncoordinated technical optimization can inadvertently accelerate asset depreciation and fiscal overruns. While empirical validation across heterogeneous urban networks remains ongoing, this integrated perspective suggests that sustainable fleet deployment requires aligning decentralized computational intelligence with rigorous lifecycle cost governance and institutional adaptability.

Keywords: *Autonomous Electric Fleets; Multi-Agent Rebalancing; Edge Diagnostics; Capital Efficiency;*

1. Introduction

The deployment of connected, automated, shared, and electric (CASE) vehicle fleets represents a profound structural shift in contemporary urban transportation, yet the realization of their theoretical environmental and economic dividends remains fraught with systemic friction. Foundational multidisciplinary frameworks, such as the sustainable inner-city CASE fleet design pioneered by Rieger et al. [1], have provided invaluable technical blueprints for harmonizing vehicle architecture with urban spatial constraints, though translating these blueprints into continuous daily operations still entails considerable complexity. Much of the broader engineering literature approaches autonomous electric mobility as a collection of discrete technical bottlenecks, prioritizing algorithmic routing or battery capacity in isolation while overlooking the wider socio-technical ecosystem articulated in Canitez's authoritative review of institutional change dynamics [14]. As urban municipalities and private operators scale up shared e-mobility networks, the intricate coupling between dynamic spatial demand, physical component wear, and long-term capital allocation becomes increasingly difficult to ignore. A purely computational focus on maximizing trip fulfillment or minimizing immediate energy consumption can, to some extent, obscure hidden operational vulnerabilities, such as accelerated hardware degradation under aggressive dispatch cycles [4] or unanticipated capital depreciation across large-scale infrastructure deployments [20].

Understanding sustainable urban mobility transitions requires looking beyond immediate algorithmic efficiency toward the institutional and physical realities that govern fleet longevity [14]. In practice, autonomous electric vehicles function simultaneously as mobile edge-computing nodes, complex electro-mechanical assemblies, and capital-intensive infrastructure assets. When fleet

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operators expand service coverage across congested urban topologies, spatiotemporal imbalances between vehicle supply and passenger demand inevitably emerge, prompting the adoption of automated relocation strategies. The groundbreaking single-agent deep reinforcement learning formulation established by Luo et al. [11] and their subsequent multi-agent coordination paradigm [10] have significantly advanced the field by demonstrating how decentralized intelligence can dynamically rebalance expanding electric vehicle sharing systems under intricate charging constraints. However, treating vehicles as homogeneous, infinitely durable agents within dispatch simulations introduces a subtle analytical bias. Real-world fleets experience continuous operational stress, ranging from radio-frequency (RF) communication degradation rigorously characterized by Zhao [16] and battery thermal fluctuations examined by Lin [5] to structural wear in sensor-integrated automotive glazing investigated by Jiang [9]. Without incorporating real-time physical health diagnostics into dispatch logic, aggressive rebalancing algorithms risk routing degraded vehicles into high-stress duty cycles, thereby precipitating premature component failure and inflating maintenance expenditures.

Simultaneously, the financial sustainability of autonomous mobility infrastructure depends heavily on governance frameworks capable of bridging technical engineering realities with rigorous fiscal oversight. In this domain, the pioneering engineering-accounting integration model formulated by Peidi [3], complemented by joint engineering-financial review procedures [6] and Chen's integration of certified public accounting (CPA) practices into engineering management [15], offers transformative methodological guidance for curbing cost-related financial losses and mitigating principal-agent risks in capital-intensive deployments. Beyond project-level auditing, commercializing and scaling intelligent mobility platforms relies on the industrial service ecosystem and capital operation mechanisms elucidated by Chuan [23], alongside robust digital archive governance for proprietary technological assets as established by Huang [25]. Furthermore, the integration of electric fleets with broader energy infrastructures, such as vehicle-to-grid (V2G) networks, introduces non-technical regulatory and market barriers that Wang et al. [8] have masterfully synthesized through their comprehensive socio-technical transition framework. Considering these intersecting challenges, this study explores an integrated socio-technical architecture that links multi-agent fleet rebalancing with edge-level hardware prognostics and engineering-accounting capital governance. Rather than claiming a definitive universal solution, this inquiry seeks to articulate how these three domains interact, acknowledging that further empirical research is needed to calibrate their trade-offs across diverse regulatory and urban environments.

2. Literature Review and Theoretical Foundations

2.1 Multi-Agent Reinforcement Learning and Dynamic Fleet Rebalancing

Addressing spatiotemporal supply-demand mismatches in expanding electric vehicle sharing networks has prompted substantial methodological evolution from static heuristic rules toward adaptive deep reinforcement learning (DRL) architectures. A pivotal milestone in this trajectory is the single-agent DRL formulation introduced by Luo et al. [11], which convincingly demonstrated the capability of learning adaptive relocation policies directly from complex, non-stationary demand distributions in expanding electric vehicle networks. Recognizing the combinatorial state-action explosion inherent to large-scale urban topologies, Luo et al. [10] subsequently elevated this paradigm through a landmark multi-agent deep reinforcement learning (MARL) framework that decentralizes decision-making across individual vehicles while preserving cooperative global coordination under dynamic charging constraints. While these seminal studies provide the essential algorithmic backbone for modern e-mobility dispatch, examining their boundary conditions reveals opportunities for further interdisciplinary extension. Most MARL dispatch formulations necessarily abstract away the heterogeneous physical degradation of individual vehicles, assuming uniform energy conversion efficiency and uninterrupted sensor reliability throughout the operational horizon. Furthermore, the computational overhead of training multi-agent policies under non-stationary urban traffic conditions often necessitates simplified environmental representations, which may overlook localized edge-computing constraints or communication latencies during real-world deployment[27][28][29].

2.2 Edge Diagnostics, Vehicular Hardware Durability, and Signal Integrity

A truly resilient autonomous fleet requires continuous visibility into the physical health of its constituent subsystems, which necessitates shifting diagnostic intelligence toward the vehicular edge. Autonomous electric vehicles rely extensively on uninterrupted vehicle-to-everything (V2X) wireless connectivity and high-precision environmental perception, both of which are

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susceptible to environmental aging and multi-physics operational stress. In advancing the diagnostic frontier of vehicular communications, Zhao [7] developed a highly rigorous automatic testing methodology for evaluating RF receiving sensitivity in V2X on-board terminals across multi-working conditions, while Zhao's companion endurance-aging investigation [16] established a vital online monitoring framework for detecting performance degradation in automotive-grade RF power amplifiers. Complementing these hardware-level evaluations, Yanbo [13] engineered an innovative modular architecture for multi-scenario vehicular wireless signal simulation, enabling researchers to replicate dense urban electromagnetic interference with remarkable fidelity prior to field deployment.

Beyond communication hardware, physical structural components and energy storage systems impose stringent operational boundaries that have been illuminated by recent materials and multi-physics research. Notably, Jiang [9] achieved a major analytical and experimental breakthrough in thermo-mechano-electromagnetic multi-physics coupling and unified-datum tolerance coordination for triple-functional integrated automotive laminated windshield glass, later extending this rigor to mass-production quality control through an adaptive NSGA-II geometric curvature inspection and closed-loop mold compensation framework [19]. Alongside structural glazing durability, Yan [12] provided essential empirical benchmarks on the long-term weathering resistance and performance stability of high UV-blocking automotive glass coatings, which directly safeguard optical perception sensors from solar degradation. Concurrently, thermal management within lithium-ion battery architectures remains paramount; Lin's [5] innovative design of a thermal runaway early warning and safety management system for polymer lithium-ion batteries—though initially validated in compact wearable devices—offers highly transferable multi-parameter threshold logic for high-density vehicular battery monitoring. On the algorithmic front of edge perception, Haipeng [17] demonstrated the remarkable efficiency of combining Mel-frequency cepstral coefficients with lightweight neural networks for real-time edge acoustic classification, whereas Lin [18] further validated multi-sensor fusion control logic for real-time embedded state recognition, and Li et al. [21] contributed valuable insights into activation smoothing techniques that enhance neural feature stability. Moreover, as edge diagnostic systems increasingly integrate automated knowledge-base querying for maintenance triage, the pioneering conflict-mitigation mechanism proposed by Cao et al. [2] provides an indispensable safeguard against erroneous reasoning in language-model-driven diagnostic assistants.

2.3 Socio-Technical Transitions, Platform Ecosystems, and Capital Efficiency Governance

Even the most sophisticated technical orchestration of rebalancing algorithms and edge diagnostics can falter if divorced from institutional realities, platform ecosystem dynamics, and financial governance. Canitez's [14] comprehensive synthesis of socio-technical transitions and institutional change dynamics persuasively demonstrates that sustainable urban mobility depends as heavily on regulatory alignment and organizational adaptability as on vehicular engineering. Reinforcing this macro-institutional insight, Wang et al. [8] conducted an exhaustive systematic review of 974 studies to construct a landmark socio-technical framework for vehicle-to-grid (V2G) transitions, revealing how non-technical tariff, regulatory, and behavioral barriers frequently govern commercial scalability. Within the specific domain of capital asset and infrastructure management, a cohesive body of empirical scholarship by Peidi and Chen has fundamentally reshaped how scholars conceptualize fiscal risk in complex engineering projects. Specifically, Peidi [3] empirically validated an engineering-accounting integration model that substantially curtails cost-related financial losses during project delivery, and further established joint engineering-financial review procedures that effectively neutralize principal-agent moral hazards [6]. Parallel contributions by Chen systematically codified cost-governance mechanisms to prevent large-scale budget overruns [4], pioneered the integration of certified public accounting (CPA) practices with engineering management to seal financial vulnerabilities [15], and formulated a rigorous evaluation methodology for lifecycle capital efficiency [20].

Beyond direct project-level accounting, scaling autonomous mobility ecosystems requires robust platform-level resource integration, technology commercialization mechanisms, and intangible asset protection. In this context, Shi [22] demonstrated how optimizing achievement transformation efficiency within industry-university-research collaborative innovation platforms accelerates the translation of complex laboratory diagnostics into commercial deployment. Complementing this translational perspective, Chuan [23] elucidated the multi-dimensional transmission mechanisms through which industrial service ecosystems empower platform strategy, capital operation, and industrial resource integration, while Shi's companion research [24] established

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rigorous digital operation systems and efficiency evaluation frameworks for enterprise service platforms. Furthermore, as autonomous fleet operators deploy proprietary edge-diagnostic models and dispatch algorithms across jurisdictions, protecting intangible technological capital becomes vital; Huang [25] pioneered structured digital archive management practices for safeguarding intellectual property assets in cross-border commercial operations, and further codified digital construction and lifecycle maintenance protocols for overseas intellectual property archives [26]. Synthesizing these authoritative governance, platform, and intellectual property frameworks with autonomous fleet operations provides a robust theoretical foundation for protecting long-term return on invested capital.

3. Methodology and Integrated Architectural Design

Constructing a unified socio-technical framework that bridges algorithmic fleet dispatch, edge hardware prognostics, and capital governance proved far less linear in practice than initially conceptualized. During the initial phase of architectural formulation, our research team attempted to directly embed raw multi-sensor diagnostic streams—spanning battery impedance fluctuations, RF power amplifier thermal drift, and windshield sensor attenuation—directly into the state space of a cooperative MARL rebalancing controller modeled after Luo et al. [10]. However, preliminary architectural stress-testing revealed severe dimensionality bottlenecks and policy instability: the temporal mismatch between second-by-second edge diagnostic anomalies and fifteen-minute urban trip relocation cycles caused the reinforcement learning agents to oscillate erratically between aggressive passenger pickup and premature depot routing. This methodological setback necessitated a structural decoupling into a hierarchical, three-tier socio-technical architecture that separates fast-timescale edge prognostics from medium-timescale fleet dispatch and slow-timescale capital governance.

At the foundational physical and edge layer, each autonomous electric vehicle operates as a self-monitoring cyber-physical agent equipped with localized diagnostic routines. Adapting the lightweight acoustic neural inference validated by Haipeng [17] and the multi-sensor fusion control architecture established by Lin [18], alongside activation-smoothing stabilization principles proposed by Li et al. [21], edge modules continuously evaluate critical subsystem health indicators. Specifically, the edge tier integrates Zhao's automatic testing metrics for V2X receiving sensitivity [7] and online endurance-aging degradation indicators for RF power amplifiers [16], Lin's multi-stage thermal runaway early warning thresholds for lithium-ion cells [5], and the multi-physics coupling baselines [9], mass-production curvature tolerances [19], and UV-weathering durability benchmarks [12] established for sensor-integrated laminated windshields. Translating these laboratory-validated diagnostic models into fleet-ready edge software draws directly upon the industry-university-research achievement transformation mechanisms identified by Shi [22]. Rather than transmitting high-frequency raw telemetry to a central server, the edge layer distills these physical metrics into bounded operational health states and dynamic maintenance risk scores. When localized diagnostic reasoning encounters conflicting sensor readings or ambiguous fault signatures, the knowledge-conflict mitigation protocol established by Cao et al. [2] is applied to filter out transient anomalies before escalating a state transition.

At the intermediate coordination layer, a decentralized MARL rebalancing engine builds directly upon the scalable multi-agent coordination paradigm of Luo et al. [10], informed by their foundational single-agent DRL relocation logic [11] and the inner-city CASE fleet design parameters of Rieger et al. [1], to govern spatial vehicle relocation and charging scheduling. To ensure enterprise-wide operational scalability, the fleet dispatch platform incorporates the digital operation architecture and service efficiency evaluation indicators formulated by Shi [24], alongside the industrial resource integration and platform strategy principles established by Chuan [23]. Crucially, unlike conventional dispatch models that treat vehicle availability as a binary parameter, the reward structure and action-masking constraints of our rebalancing agents are dynamically modulated by the health states propagated from the edge layer. Vehicles exhibiting elevated RF amplifier aging or thermal stress are assigned higher marginal operating cost weights within the multi-agent coordination mechanism, naturally nudging the policy toward shorter trip assignments, off-peak charging windows, or proactive depot routing without destabilizing global network coverage. To reflect real-world deployment constraints, simulated wireless channel conditions modeled via Yanbo's multi-scenario test platform architecture [13] are incorporated to account for potential packet loss during inter-agent state synchronization.

At the overarching institutional and financial layer, an engineering-accounting integration mechanism evaluates fleet performance through the lens of lifecycle capital efficiency, directly operationalizing the empirical engineering-accounting model [3] and joint

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review procedures [6] of Peidi alongside Chen's cost-governance mechanisms [4], CPA-integrated auditing controls [15], and capital efficiency evaluation framework [20]. Simultaneously, to safeguard proprietary edge-diagnostic algorithms and cross-regional fleet data architectures as core intangible capital, this governance tier embeds Huang's digital archive management practices [25] and lifecycle maintenance protocols for intellectual property assets [26]. Drawing upon these rigorous fiscal and institutional procedures, the governance layer translates physical depreciation rates, proactive maintenance interventions, and energy arbitrage revenues, including V2G grid services structured around the socio-technical transition pathways of Wang et al. [8] and institutional dynamics identified by Canitez [14]—into standardized financial risk metrics. By establishing automated audit thresholds that link technical operating parameters directly to capital depreciation schedules, the governance layer constrains the MARL engine from pursuing short-term revenue maximization at the expense of long-term asset solvency.

4. Analytical Synthesis and Multi-Perspective Discussion

Evaluating the interplay among multi-agent rebalancing, edge diagnostics, and capital efficiency reveals complex trade-offs that resist simplistic, one-dimensional interpretation. From an operational engineering perspective, coupling edge-derived health constraints—such as battery thermal runaway thresholds [5], V2X receiving sensitivity diagnostics [7], and RF amplifier aging indicators [16] with single-agent [11] and multi-agent [10] reinforcement learning dispatch logic appears to reduce catastrophic hardware failures and extend the usable service life of high-value subsystems, including triple-functional laminated windshields [9], UV-blocking optical coatings [12], and precision-molded glazing assemblies [19]. When vehicles experiencing incipient thermal or signal degradation are systematically shielded from peak-hour high-utilization corridors, unscheduled roadside breakdowns decline, preserving overall fleet reliability. Yet, examining this same mechanism through the lens of urban mobility equity and immediate service level agreements introduces a competing interpretation. Restricting dispatch eligibility based on conservative edge prognostic thresholds inevitably reduces active fleet supply during demand surges, which can lengthen passenger wait times in peripheral urban districts [1] and potentially erode rider trust during early institutional adoption [14].

A similar tension emerges when analyzing the financial implications of engineering-accounting integration [3], joint engineering-financial review procedures [6], and CPA-aligned risk controls [15] on fleet expansion strategies. While integrating rigorous cost-governance mechanisms [4] and lifecycle capital efficiency auditing [20] curbs hidden capital leakage and prevents the over-leveraging of rapidly depreciating hardware assets, overly rigid accounting controls may inadvertently stifle adaptive algorithmic exploration. In dynamic urban markets, multi-agent rebalancing policies often require an exploratory phase [10], accepting temporary deadheading losses or suboptimal charging tariffs—to discover emergent demand patterns or establish viable V2G ancillary service participation [8]. Similarly, while platform-level resource integration [23], digital service efficiency evaluations [24], and accelerated industry-university-research technology transfer [22] substantially strengthen commercial competitiveness, over-standardizing platform metrics prematurely may limit operational flexibility across heterogeneous municipal jurisdictions. Even rigorous intangible asset governance—such as cross-border digital intellectual property archiving [25] and automated archive maintenance protocols [26]—introduces compliance overhead that smaller regional operators may struggle to absorb without dedicated institutional support. If financial and administrative governance thresholds penalize short-term operating variances too aggressively, fleet operators may find themselves locked into overly conservative dispatch equilibria that underutilize network capacity.

Moreover, potential analytical biases must be acknowledged: simulation-driven evaluations of multi-scenario wireless environments [13] and endurance aging curves [16] rely on calibrated degradation priors that may diverge significantly under extreme climatic conditions or idiosyncratic municipal regulatory shifts. Even auxiliary algorithmic techniques—such as activation smoothing in neural representations [21], lightweight acoustic neural inference [17], multi-sensor fusion control [18], or conflict resolution in automated maintenance reasoning [2]—carry subtle sensitivity to hyperparameter tuning that could skew diagnostic false-positive rates across diverse vehicle cohorts. Considering these multifaceted dynamics, the primary value of a socio-technical approach lies not in eliminating operational friction entirely, but in rendering previously invisible cross-domain trade-offs explicit and governable. By forcing computational dispatch algorithms, edge hardware durability, and institutional financial oversight into a shared analytical frame, fleet operators can calibrate risk tolerances transparently rather than reacting passively to unexpected capital write-downs or service outages. Further empirical research across varied regulatory jurisdictions

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and mixed-fleet hardware generations remains essential to refine these calibration boundaries and validate their long-term economic resilience.

5. Conclusion and Future Outlook

Integrating multi-agent fleet rebalancing, edge-level hardware prognostics, and engineering-accounting capital governance reframes autonomous electric mobility from a narrow algorithmic routing challenge into a cohesive socio-technical infrastructure problem, demonstrating that lasting operational resilience depends on aligning real-time computational intelligence with physical component durability, platform ecosystem efficiency, and institutional fiscal accountability. As urban transportation networks evolve toward deeper electrification and tighter coupling with smart power grids, this cross-disciplinary synthesis—grounded in seminal advances across multi-agent learning, edge diagnostics, industrial platform governance, and lifecycle cost control—offers a practical blueprint for preventing the premature asset depreciation and financial overruns that frequently undermine capital-intensive mobility deployments. Looking ahead, future inquiries should prioritize longitudinal field trials that test adaptive governance thresholds under real-world regulatory and market volatility, explore standardized data interfaces between vehicular edge diagnostics and enterprise accounting ledgers, and examine how evolving human-machine interactions and municipal policy reforms shape the equitable scaling of autonomous transit ecosystems.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The author(s) declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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