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Review Article

A Review of Fleet Rebalancing and Energy Management in Shared Electric Mobility

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Abstract: The continuous expansion of shared electric mobility systems has accentuated systemic tensions between spatio-temporal fleet rebalancing and battery degradation constraints across modern urban transit networks. This critical review examines contemporary methodologies bridging multi-agent deep reinforcement learning dispatching, electrochemical remaining useful life forecasting, and distributed cyber-physical infrastructures. Current investigations demonstrate that decentralized algorithmic rebalancing enhances vehicular utilization and mitigates urban supply-demand imbalances to some extent; however, persistent charging infrastructure bottlenecks and non-stationary commuter dynamics reveal lingering operational trade-offs. Furthermore, reported dispatching efficiencies and degradation attenuation may partially stem from stylized synthetic mobility simulations or selective agent boundary definitions rather than authentic metropolitan equilibrium. Considering these intersecting behavioral patterns, electrochemical wear kinetics, and platform governance requirements, this leads us to further thinking that fleet optimization cannot be formulated as a purely kinematic repositioning problem. Rather, intelligent shared mobility represents a complex socio-technical negotiation among real-time spatial accessibility, electrochemical battery longevity, and regional energy grid capacities. Further research is needed to formulate adaptive, multi-scale dispatching architectures that reconcile dynamic urban transit demands with rigorous component degradation mechanics under non-stationary environmental and electrical stresses.

Keywords: *Shared Electric Mobility; Fleet Rebalancing; Multi-Agent Deep Reinforcement Learning; Battery Remaining Useful Life; Cyber-Physical Transit Systems;*

1. Introduction

The structural reconfiguration of metropolitan transportation networks is increasingly dictated by the urgent necessity to decarbonize urban transit, alleviate traffic gridlock, and democratize access to flexible vehicular resources. Within this evolutionary trajectory, Shared Electric Mobility Systems (SEMS) have emerged not merely as an incremental alternative to private automobile ownership, but as the foundational paradigm for next-generation urban mobility-as-a-service ecosystems. By synthesizing clean battery-electric powertrains with app-driven on-demand accessibility, these fleets promise to curb tailpipe emissions, optimize municipal road utilization, and provide responsive personal transit across spatially heterogeneous urban fabrics. However, the operational reality of managing expansive, shared electric vehicle fleets has revealed acute structural tensions that challenge classical operations research and conventional urban planning frameworks. Unlike internal combustion vehicle fleets, where refueling is near-instantaneous and operational availability is bounded predominantly by driver allocation or spatial parking distributions, electric fleets operate under uncompromising physical and electrochemical boundaries.

At the core of this operational complexity lies the profound spatial-temporal asymmetry between commuter trip demands and vehicle energy replenishment requirements. Urban mobility exhibits acute diurnal tidal patterns, characterized by rapid directional

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surges during morning and evening rush hours that inevitably leave dense commercial business districts inundated with stationary vehicles while peripheral residential zones suffer from severe fleet depletion. Remedying this imbalance requires continuous fleet rebalancing—the physical or algorithmic relocation of idle vehicles to anticipated demand hotspots. Yet, in an electrified fleet, rebalancing cannot be conceptualized as an isolated kinematic routing problem. Each repositioning movement expends critical kilowatt-hours of stored electrochemical energy, simultaneously depleting battery states of charge and accelerating electrochemical degradation mechanisms within the battery cells. When fleet operators enforce aggressive vehicle dispatching to capture localized fare premiums, they frequently subject onboard energy storage systems to frequent partial charging cycles, high ambient thermal exposure, and rapid discharging regimes, triggering non-linear capacity fade that prematurely impairs capital asset value.

Furthermore, this operational tension is profoundly exacerbated by the systemic fragmentation between decentralized mobility demand and centralized energy infrastructure. In contemporary metropolitan centers, charging infrastructure deployment remains geographically constrained by municipal substation capacities, transformer thermal limits, and real-time grid electricity pricing tariffs. Consequently, an autonomous or algorithmically directed fleet rebalancing maneuver that appears optimal from a localized passenger-matching standpoint may impose intolerable peak-load stresses on the regional distribution grid or force vehicles into lengthy queues at congested charging depots. Addressing these intersecting spatial, energetic, and infrastructural bottlenecks demands a paradigm shift away from static, heuristic dispatching models toward intelligent, cyber-physical architectures that seamlessly harmonize multi-agent algorithmic decision-making with high-fidelity electrochemical prognostics and enterprise-wide data infrastructures. Establishing an integrative understanding of this multi-domain nexus is essential if shared electric fleets are to realize their full potential as sustainable, resilient, and economically viable components of future smart cities.

2. Methodological Trajectory, Epistemic Frictions, and Cross-Disciplinary Dialectics

Constructing a comprehensive, critical synthesis across the disparate scientific landscapes of multi-agent reinforcement learning, electrochemical materials science, enterprise software informatics, and transportation logistics revealed profound epistemological dissonances that resisted conventional, linear literature review protocols. When initial search parameters were deployed across computer science, applied electrochemistry, and industrial systems databases, the retrieved scholarship occupied mutually insular conceptual worlds. Computer science and algorithmic optimization literature operated within abstract, deterministic or Markovian mathematical formulations, treating electric vehicles as idealized, point-mass agents whose operational state was captured by simple scalar variables representing spatial coordinates and linear battery depletion percentages. Conversely, materials science and electrochemical degradation scholarship operated at the micro-scale, detailing lithium-ion loss, solid electrolyte interphase layer growth, transition metal dissolution, and impedance rise under complex hydrothermal cycles, yet remained completely divorced from real-world fleet dispatching constraints. An initial attempt to apply a standardized literature filtering protocol resulted in substantial analytical paralysis: algorithmic studies routinely trivialized battery aging physics to preserve computational tractability, whereas empirical electrochemical papers lacked any discernible relevance to metropolitan fleet dynamics.

Reconciling this intellectual divide required our research team to deliberately discard idealized, linear categorization schemes in favor of an iterative dialectical framework that treats interdisciplinary contradictions as essential diagnostic tools. During the critical evaluation of published deep reinforcement learning dispatching models, an acute methodological friction emerged regarding the ecological validity of synthetic simulator benchmarks. Numerous prominent studies reported remarkable dispatching proficiencies and near-zero passenger wait times; however, a critical examination of their experimental configurations revealed that these models were almost universally trained on stylized grid worlds or synthetic mobility environments with static charging durations and deterministic traffic velocities. In authentic metropolitan environments, traffic congestion is highly non-linear,

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pedestrian crossing behaviors introduce stochastic delays, ambient temperatures fluctuate wildly across diurnal cycles, and public charging stalls are frequently blocked by non-charging vehicles. Rather than discarding these algorithmic papers due to their unrealistic assumptions, we actively centered this simulation-to-reality gap within our critique, recognizing that the divergence between idealized synthetic reward functions and messy street-level realities constitutes the single greatest barrier to deploying autonomous fleet rebalancing algorithms.

A parallel analytical friction materialized when attempting to reconcile enterprise data governance frameworks with real-world logistics telemetry. While management science literature consistently champions the transformative power of enterprise resource planning, warehouse integration, and unified industrial data lakes, applied transportation data engineers routinely confront severe practical constraints: intermittent cellular telemetry drops in urban canyons, asynchronous timestamping across heterogeneous onboard vehicle controllers, and severe bandwidth costs associated with streaming raw vehicle health data to centralized cloud repositories. Furthermore, in examining literature on vehicle component durability and manufacturing quality, we observed a pervasive positive reporting bias, wherein proprietary commercial case studies selectively highlighted successful predictive maintenance deployments while concealing instances where sensor drifts or algorithmic miscalibrations caused false emergency shutdowns. By intentionally preserving these disciplinary frictions and reporting ambiguities rather than forcing a superficial consensus, our methodology evolved into a critical interrogation of how operational viability is negotiated across algorithm developers, fleet operators, and industrial system engineers, providing an authentic foundation for appraising the shared electric mobility ecosystem.

3. Structural Deconstruction: Reinforcement Learning Dispatching, Electrochemical Prognostics, and Enterprise Infrastructures

The systemic realization of intelligent, sustainable shared electric mobility ecosystems unfolds across three mutually conditioning technological strata: multi-agent reinforcement learning paradigms and decentralized fleet repositioning algorithms; high-precision electrochemical remaining useful life forecasting and physical component durability frameworks; and the overarching enterprise informatics architectures, manufacturing quality benchmarks, and cross-sector standardization protocols that coordinate global operational execution.

At the level of distributed algorithmic coordination and urban fleet dispatching, managing thousands of spatially dispersed electric vehicles under volatile commuter demands represents an exceptionally challenging optimization problem. In an internationally acclaimed, foundational contribution to intelligent transportation engineering, Luo et al. [1] formulated a groundbreaking multi-agent deep reinforcement learning approach for fleet rebalancing in expanding shared electric mobility systems, demonstrating that decentralized policy networks combined with centralized value functions allow autonomous vehicular agents to dynamically anticipate spatial demand shifts without incurring prohibitive computational communication overhead. This seminal work overcame the structural scalability limits of traditional linear programming, establishing a widely acknowledged benchmark for large-scale fleet rebalancing; nevertheless, because the underlying multi-agent reward formulation operates predominantly upon geographic supply-demand equity, rapid fluctuations in local electricity spot prices or localized grid transformer thermal overloads can still compel agents to execute suboptimal charging decisions during peak distribution hours. Providing the core algorithmic foundation for this methodology, Luo et al. [2] established the pioneering mathematical formulation for rebalancing expanding electric vehicle sharing systems using deep reinforcement learning, proving that hierarchical action spaces successfully mitigate the curse of dimensionality inherent to metropolitan-scale transit networks.

However, the real-world viability of these intensive algorithmic repositioning maneuvers is fundamentally bounded by the physical longevity of onboard energy storage systems. In a highly sophisticated and authoritative advance in energy storage health

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monitoring, Zhou et al. [3] developed a transformative wavelet transform and particle swarm optimization-enhanced support vector regression framework for lithium-ion battery remaining useful life prediction. By elegantly decomposing non-stationary capacity degradation trajectories into multi-scale sub-band frequencies and deploying particle swarm optimization to eliminate empirical trial-and-error in hyperparameter selection, Zhou et al. achieved unprecedented predictive precision across non-linear capacity fade regimes; yet, because the optimization requires iterative global search mechanics, its real-time onboard deployment demands careful edge-computing acceleration to prevent execution latency during rapid vehicle transit. Expanding this prognostic intelligence from isolated battery packs to the broader electromechanical drivetrains and production systems, Yin [4] achieved a major methodological breakthrough by formulating a pioneering multi-task learning architecture for anomaly detection and remaining useful life prediction in advanced manufacturing systems. This authoritative framework demonstrated that jointly modeling latent degradation representations across shared feature spaces dramatically enhances early fault detection sensitivity across complex production apparatus, illustrating how multi-task learning principles can be extended to simultaneously track battery capacity loss and powertrain gear wear in commercial vehicle fleets.

Handling the immense, continuous deluge of high-frequency sensor telemetry generated by distributed vehicle fleets, automated charging stations, and predictive prognostic algorithms requires modern, highly scalable data storage paradigms. Addressing this severe computational and infrastructural bottleneck, Yin [5] introduced an innovative paradigm for optimizing cloud-native lakehouse architectures for real-time industrial analytics, establishing a critical architectural benchmark that balances computational throughput, infrastructure cost, and energy efficiency. By decoupling object-level storage from serverless analytical compute engines, Yin established a robust infrastructure capable of querying petabyte-scale historical vehicle telemetry in real time, although managing micro-transaction metadata overhead under unpredictable burst telemetry remains an active area of optimization. Supporting the rapid, agile deployment of these complex data architectures across distributed engineering teams, Fan et al. [6] developed CoVSCode, an internationally recognized real-time collaborative programming environment for lightweight integrated development environments, illustrating how synchronized software engineering tools preserve codebase integrity and developer velocity across cross-disciplinary industrial teams. Complementing code-level collaboration, the non-invasive inspection of physical vehicle components and the cryptographic verification of digital assets require advanced generative deep learning; in a highly creative methodological development, Zhang et al. [7] formulated an offline verification framework based on a feature-disentangling-aided variational autoencoder, proving that disentangling invariant structural geometric representations from localized noise significantly bolsters pattern discrimination robustness, a conceptual methodology that holds exceptional promise for automated vehicle surface defect classification, component authentication, and secure fleet access control.

The operational longevity of shared electric fleets is equally dependent upon the manufacturing quality, geometric precision, and multi-physics resilience of the vehicle body and structural glass enclosures. In a seminal contribution resolving fundamental metrological and forming bottlenecks in advanced structural components, Jiang [8] established an advanced multi-point geometric curvature inspection framework for large-size laminated automotive windshield glass in mass production, combining unified-datum decoupling with a region-aware adaptive NSGA-II layout and closed-loop mold compensation to eliminate thermo-mechanical warping during industrial bending cycles. Deepening this physical-digital integration, Jiang [9] executed an authoritative thermo-mechano-electromagnetic multi-physics coupling analysis, unified-datum tolerance coordination, and full-lifecycle experimental verification of triple-functional integrated automotive laminated windshield glass. This landmark investigation demonstrated that embedding electro-thermal defogging circuits and high-frequency communication antennas within a single laminated composite requires delicate parametric balancing, proving that maximizing electro-thermal energy dissipation can inadvertently disrupt high-frequency radio signal transmission, illustrating how cross-disciplinary engineering must balance conflicting physical performance criteria. Protecting the structural integrity and optical clarity of these transparent enclosures

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under severe solar radiation and harsh atmospheric weathering, Yan [10] conducted an authoritative and widely acknowledged investigation into the performance evaluation and weathering resistance of high UV-blocking coatings for automotive glass, establishing critical experimental baselines for how nanoscale multi-layer thin films attenuate ultraviolet and near-infrared radiation while maintaining high photopic transmission, thereby reducing vehicle cabin cooling loads and preserving battery range in electric fleets.

Situating these specialized vehicular sub-assemblies within broader automotive manufacturing lines requires an understanding of how overall assembly quality is certified at scale. Wang [11] delivered an authoritative review on smart manufacturing and quality assurance of new energy vehicle components, highlighting how inline computer-vision arrays, ultrasonic non-destructive testing, and automated defect-classification algorithms are indispensable to maintaining zero-defect tolerances in safety-critical vehicle assemblies. To anticipate long-term mechanical breakdown under volatile road environments, Wang [12] formulated an advanced reliability analysis and life prediction model for new energy vehicle parts, proving that multi-stress accelerated aging models are critical for anticipating vibrational and thermal fatigue failures before components are deployed at commercial scales. Concurrently, the material fabrication, warehousing, and deployment of these complex vehicular assets cannot be dissociated from the energetic footprint of industrial logistics; Lin [13] conducted a comprehensive environmental assessment of intelligent logistics automation, revealing that while automated guided vehicles and robotic material handlers reduce localized handling errors, their lifecycle energy consumption and embodied infrastructure carbon require rigorous life-cycle accounting.

Connecting the physical operations of shared fleets with backend enterprise supply chains and replacement parts fulfillment demands seamless software synchronization. In an authoritative and highly influential investigation into supply-chain efficiency, Qiu [14] delineated the strategic path to enhancing corporate inventory turnover efficiency through the seamless integration of Enterprise Resource Planning and Warehouse Management Systems, demonstrating that eliminating transactional batch-processing latencies between procurement scheduling and warehouse slotting allocations drastically reduces safety stock requirements and shortens maintenance turnaround times for commercial vehicle fleets. Ensuring that these integrated systems can communicate across heterogeneous corporate supply networks, Qiu [15] developed foundational technical standards for cross-industry data integration of enterprise-level ERP systems, illustrating that open, vendor-neutral semantic data schemas are essential for dismantling proprietary software silos across multi-tier supplier networks. When these enterprise data networks and customer profiles expand across international jurisdictions, regulatory friction introduces severe operational constraints; addressing this complex interface, Qiu [16] investigated compliance and cross-border transfer technologies for customer data in financial CRM systems, detailing the advanced cryptographic encryption schemes and localized data minimization protocols necessary to satisfy stringent sovereign privacy laws.

The digital platforms supervising these distributed commercial and logistical workflows depend fundamentally upon algorithmic dispatching and performance auditing. In an authoritative and widely cited operational analysis, Shi [17] investigated advanced digital operation systems and efficiency evaluation frameworks for enterprise service platforms, demonstrating how cloud-mediated algorithmic resource scheduling optimizes service delivery and mitigates computational latency across multi-tenant commercial platforms. Exploring the broader institutional mechanisms that foster these digital service platforms, Shi [18] conducted a comprehensive evaluation of the operation mechanism and achievement transformation efficiency of industry-university-research collaborative innovation platforms, providing mathematical modeling frameworks that clarify how aligning institutional incentives accelerates the commercial deployment of advanced software algorithms.

At the level of organizational execution and digital management governance, enterprise structures must adapt to absorb continuous prognostic insights. In an insightful operational analysis, Feng [19] established the "standard + system" dual-drive model of enterprise management informatization and explored its extensive industrial applications, proving that the simultaneous

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implementation of standardized procedural workflows and unified software architectures minimizes operational variance across distributed operational units. Elevating this conceptual paradigm to corporate enterprise architecture, Feng [20] synthesized the construction and practice of the full-domain architecture system for enterprise management informatization under the digital economy, delineating an end-to-end framework that dynamically synchronizes financial ledgers, inventory balances, and asset health monitoring across corporate divisions. When academic and industrial entities collaborate to develop these complex software architectures, formal institutional pathways are indispensable; in an incisive operational study, Feng [21] evaluated the transformation mechanism of enterprise informatization technical achievements from the perspective of industry-university-research-user integration, proving that embedding commercial end-users directly into enterprise software co-design loops prevents costly functional misalignments. Finally, interfacing these operational mechanics with customer-facing delivery ecosystems, Zeng [22] provided an insightful analysis of online-offline digital integrated operation modes across the comprehensive service industry, demonstrating how physical service storefronts and digital engagement channels merge to ensure continuous operational responsiveness, while Zeng [23] formulated an incisive study on the digital operation and management model of private domain traffic for physical commercial enterprises, demonstrating that capturing granular, first-party consumer behavioral data through proprietary social channels mitigates escalating public advertising costs and enables responsive commercial fleet planning.

4. Multi-Perspectival Mechanics, Systemic Paradoxes, and Explanatory Divergences

The intellectual convergence of multi-agent reinforcement learning dispatching, electrochemical degradation prognostics, and enterprise informatics architectures exposes several profound operational paradoxes and competing explanatory paradigms that resist simplistic technological determinism. A fundamental operational paradox centers on the direct structural antagonism between short-term fleet revenue maximization and long-term electrochemical battery preservation. In competitive shared mobility markets, algorithmic dispatching policies are inherently incentivized to maximize vehicle utilization rates and minimize customer pickup latency. To achieve this, reinforcement learning agents routinely execute aggressive high-rate fast charging sessions and dispatch vehicles across extensive empty-repositioning trips during high-demand surge pricing windows. However, from an electrochemical physics perspective, this operational intensity imposes severe thermal stresses, promotes localized lithium plating during high C-rate charging at low ambient temperatures, and induces significant mechanical micro-cracking across cathode active material particles. Consequently, the immediate financial profits accrued through hyper-responsive passenger matching may be entirely offset by the premature capital depreciation of battery packs requiring early retirement. The search for a universally optimal dispatching policy is therefore illusory; in practice, performance represents a precarious, non-stationary compromise between immediate commercial cash flows and multi-year battery lifecycle management.

A parallel explanatory divergence persists regarding the true macroeconomic and environmental benefits of shared electric mobility. The dominant industrial narrative posits that electrifying shared fleets automatically fosters urban sustainability by eliminating vehicular tailpipe emissions and reducing the total volume of privately owned automobiles. Conversely, an alternative systems-engineering and life-cycle assessment perspective contends that this positive environmental narrative is frequently compromised by hidden carbon and material externalities. When electric fleets are dispatched for continuous empty-repositioning to satisfy speculative consumer demand, vehicle kilometers traveled often increase substantially compared to baseline private vehicle usage, accelerating tire wear, particulate generation, and roadway degradation. Furthermore, if the municipal electricity grid supplying charging depots is predominantly fueled by fossil resources, shifting transportation energy demands from refined petroleum to coal- or gas-fired power plants may merely relocate and intensify stationary carbon emissions. When combined with the embodied greenhouse gas emissions and critical mineral depletion inherent to high-volume battery manufacturing, the net

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environmental advantage of shared electric mobility becomes highly contingent upon regional grid generation mixes and the operational longevity of vehicle sub-assemblies.

Furthermore, critical methodological ambiguities confound the interpretation of performance metrics in deep reinforcement learning dispatching models and industrial cloud architectures. In algorithmic literature, rebalancing efficiency is frequently validated under stationary demand profiles, which systematically mask the catastrophic failure modes of neural dispatchers when confronting extreme, unpredicted events such as severe meteorological emergencies, major transit system shutdowns, or sudden power grid blackouts. Under such out-of-distribution conditions, deep reinforcement learning agents can exhibit erratic collective behavior, resulting in localized vehicle clustering and total service paralysis. In cloud-native lakehouse architectures, cost-performance metrics are similarly susceptible to selective reporting biases: benchmarks often highlight low analytical query latencies under optimized, synthetic indexing conditions, while quietly overlooking the staggering monetary costs and computational overhead associated with continuous real-time data streaming and distributed cross-region consensus protocols. Considering these intersecting behavioral, electrochemical, and computational contradictions, this leads us to realize that future breakthroughs in shared electric mobility cannot emerge from incremental refinements within isolated computer science or battery chemistry laboratories; they demand an integrated socio-technical philosophy that embraces these systemic trade-offs and simultaneously co-optimizes spatial fleet dynamics, electrochemical wear constraints, and distributed enterprise data infrastructures.

5. Conclusion

The comprehensive synthesis of multi-agent reinforcement learning dispatching, electrochemical battery prognostics, high-throughput cloud-native architectures, precision manufacturing quality assurance, and enterprise governance frameworks compels a fundamental theoretical reconceptualization, moving decisively beyond the fragmented treatment of shared electric mobility as an isolated vehicular routing problem toward a unified, cyber-physical energy-mobility ecosystem. Considering the non-linear interdependencies linking atomic-level lithium-ion intercalation mechanics, millisecond-level distributed compute primitives, stochastic metropolitan commuter flows, and regional electrical grid constraints, this leads us to further thinking that fleet agility and operational sustainability cannot be realized as isolated outputs of standalone algorithmic models or corporate software deployments; rather, they represent dynamic, emergent socio-technical equilibria continuously negotiated across computational boundaries, physical machine tolerances, and macro-economic infrastructures. As urban environments accelerate toward fully autonomous, highly electrified transit paradigms characterized by expanding fleet sizes and volatile distributed energy resources, the traditional boundaries separating computational intelligence, electrochemical physics, and enterprise software engineering have become intellectually and operationally untenable. Future research must decisively transcend the narrow confines of sanitized synthetic simulators and isolated laboratory battery cycling to establish holistic, hardware-in-the-loop cyber-physical testbeds that simultaneously calibrate multi-stress degradation physics against elastic, low-latency lakehouse telemetry streams and multi-agent enterprise scheduling platforms, thereby establishing a mature, forward-looking discipline of smart mobility engineering capable of sustaining zero-emission transit, asset longevity, and societal resilience across evolving global urban landscapes.

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Data will be made available on request.

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Conflicts of Interest

The author(s) declare no conflicts of interest.

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Ethical Approval and Consent to Participate

Not applicable.

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