Research Article

Fleet Coordination and Edge Hardware Resilience in Connected Electric Mobility

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***Abstract*:** Coordinating autonomous electric vehicle fleets across expanding shared mobility systems increasingly relies on multi-agent reinforcement learning architectures; nevertheless, reconciling macroscopic dispatch optimization with microscopic physical-layer hardware constraints remains methodologically vulnerable. In this study, we evaluated an integrated framework linking distributed fleet rebalancing policies with physical-layer telemetry integrity, specifically examining V2X radio-frequency degradation, multi-functional laminated enclosure tolerances, and edge battery thermal monitoring. Although simulated multi-agent scheduling attenuated localized fleet imbalances to some extent, empirical hardware-in-the-loop stress tests revealed non-linear systemic performance degradation under persistent signal attenuation and vehicular radio-frequency power amplifier aging. Complex electromagnetic-mechanical coupling across curved laminated surfaces and sensor drift further confounded telemetry accuracy, suggesting that algorithmic rebalancing benefits are partially offset by latent physical vulnerabilities. Discrepancies between theoretical dispatch convergence and physical execution latency may stem from unmodeled thermal stress or communication packet loss during dynamic vehicle handovers. These observations indicate that autonomous mobility frameworks cannot treat hardware nodes as idealized execution units. Considering the above factors, dynamic fleet management protocols must incorporate physical-layer degradation indices into reward formulations, though further research is needed to establish unified cross-layer validation across extreme environmental operational conditions.

Keywords: *Connected autonomous vehicles, Multi-agent fleet rebalancing, V2X radio-frequency telemetry, Multi-physics sensor packaging, Battery thermal safety.*

1. Introduction

The systemic evolution of urban transportation networks toward electrification and automation has fundamentally recast the problem of shared mobility from static inventory dispatch into dynamic, spatial-temporal optimization. In large-scale electric mobility-on-demand architectures, the core operational dilemma resides in mitigating chronic supply-demand misalignments caused by localized passenger origin-destination asymmetries. To address this structural friction, distributed multi-agent reinforcement learning paradigms have emerged as the prevailing algorithmic framework, demonstrating

an ability to decompose complex urban transit topologies into decentralized decision spaces. Within these computational models, autonomous vehicular agents are typically treated as idealized Markov decision process entities that observe immediate regional imbalances, evaluate continuous action spaces, and execute autonomous repositioning trajectories to maximize global transit throughput. Foundational inquiries into expanding shared electric fleets have demonstrated how multi-agent policy iteration can adaptively mitigate localized spatial shortages across extensive urban boundaries [3]. Prior theoretical formulations similarly established that deep reinforcement learning could resolve fleet imbalances during rapid network expansion under simulated operational conditions [9]. However, contemporary transportation system engineering increasingly reveals an acute ontological divide between these computational abstractions and the empirical physical reality of automotive deployment. While algorithmic research assumes instantaneous dispatch execution, negligible communication latency, and uniform hardware reliability across vehicle fleets, operational environments inevitably force algorithmic agents to interact through imperfect edge hardware nodes that are continually subjected to environmental degradation, physical enclosure interference, and severe thermal constraints.

In actual vehicle-to-everything (V2X) vehicular deployments, autonomous coordination signals cannot propagate across frictionless digital conduits; rather, they depend entirely upon the signal reception sensitivity of onboard vehicular telematics terminals. When evaluating the radio-frequency performance of V2X onboard transceivers across heterogeneous environmental conditions, Zhao established automated testing methodologies that demonstrated severe receiving sensitivity fluctuations and boundary-case communication failures under dynamic multi-path fading and interference [2]. Neglecting these empirical radio-frequency degradation patterns in algorithmic reward formulations creates an acute vulnerability, wherein reinforcement learning policies issue dispatch mandates across communication channels that may be momentarily degraded, leading to uncoordinated vehicle trajectories and compromised network efficiency.

The vulnerability of onboard telemetry is further compounded by structural manufacturing tolerances and the physical integration of sensor enclosures. In modern connected vehicles, antenna arrays and optical sensing suites are increasingly embedded within large-size multi-functional laminated windshield glass to preserve aerodynamic styling and protect sensitive hardware from external environmental exposure. However, this functional integration introduces severe multi-physics coupling complexities. In an exhaustive structural analysis of automotive laminated assemblies, Jiang demonstrated that high-curvature laminated glass components experience complex thermo-mechano-electromagnetic coupling, wherein local thermal gradients, residual manufacturing stresses, and geometric curvature deviations directly alter the electromagnetic permittivity of the enclosure [5]. Such physical variations distort radio-frequency beamforming patterns and attenuate high-frequency communication signals before they reach onboard processing units. While advanced manufacturing methodologies achieve substantial geometric tolerance control through unified-datum decoupling and adaptive genetic mold compensation algorithms in mass-production environments [4], operational weathering, ultraviolet degradation, and long-term thermal cycling inevitably alter optical clarity and surface dielectric properties over the vehicle lifecycle [8].

Simultaneously, the physical viability of continuous edge autonomy is constrained by the thermal and electrical limitations of onboard energy storage and computing modules. Deploying high-frequency multi-agent coordination models alongside local perception algorithms imposes substantial computational burdens on vehicular edge hardware, generating significant localized thermal dissipation. When autonomous edge devices operate under sustained processing loads, the thermal reliability of compact

lithium-ion power sources becomes a critical point of systemic failure. In his investigations into compact monitoring terminals, Lin documented how internal thermal runaway processes in polymer lithium-ion batteries can initiate abruptly under sustained operational aging and localized heat concentration, necessitating predictive multi-sensor early warning architectures [25]. When these power-dense, space-constrained architectures are deployed in vehicular edge environments, early fault detection often requires interpreting nuanced acoustic and mechanical degradation features. Haipeng demonstrated that extracting spectral feature coefficients through lightweight neural networks provides effective, localized acoustic pattern recognition without overwhelming edge computational budgets [1]. Integrating these micro-scale sensing and control strategies into multi-sensor embedded platforms, as demonstrated in Lin's intelligent hardware control designs [11], underscores that autonomous edge nodes require continuous physical-state self-monitoring. Considering these cascading physical-layer realities, macroscopic fleet rebalancing policies cannot remain divorced from microscopic telemetry degradation, dielectric enclosure fluctuations, and onboard energy safety.

2. Research Design, Methodological Adjustments, and Practical Constraints

Constructing an experimental apparatus capable of bridging macroscopic multi-agent reinforcement learning algorithms with microscopic physical-layer hardware metrics required iterative methodological redesigns. The foundational research plan was originally conceived around an idealized, end-to-end hardware-in-the-loop (HIL) simulation testbed, wherein distributed software agents executing dispatch algorithms would communicate via software-defined radios connected directly to operational vehicular telematics units mounted within environmental stress chambers. In theory, this closed-loop architecture was intended to subject executing multi-agent policies to real-time physical-layer perturbations. However, early pilot implementations revealed insurmountable architectural bottlenecks. Synchronizing macroscopic multi-agent training cycles—which process spatial-temporal urban traffic dynamics over simulated hours—with microscopic radio-frequency wave propagation and microsecond-level hardware interrupt vectors produced severe time-domain dilation. The computational overhead of running full-scale electromagnetic multi-physics solvers alongside multi-agent gradient updates caused the simulation clocks to decouple, rendering real-time closed-loop training computationally intractable on our laboratory edge infrastructure.

To resolve this dimensional impasse, we restructured the methodology into a staged, hybrid empirical framework. Rather than forcing simultaneous co-simulation, we established a parameterized hardware degradation mapping pipeline. Microscopic physical-layer testing was decoupled and executed across specialized benchtop testbeds, where physical automotive telematics transceivers, high-curvature laminated enclosure specimens, and instrumented lithium-ion edge power units were subjected to rigorous empirical stress protocols. In capturing vehicular wireless channel dynamics, our methodology drew upon the modular architecture designs for multi-scenario vehicular wireless signal simulation platforms established by Yanbo, which enabled realistic recreation of dynamic multipath attenuation, Doppler shifts, and shadowing without requiring full-scale vehicle track deployment [21]. To ensure software synchronization and code execution reliability across heterogeneous edge nodes during benchmark testing, experimental toolchains incorporated lightweight real-time collaborative development runtime concepts adapted from modern distributed IDE frameworks [12]. Furthermore, to maintain consistency across heterogeneous experimental layers, we adapted a three-dimensional standardization framework originally conceptualized for multi-tier technical informatization to harmonize data structures between RF measurements, material stress models, and algorithmic state spaces [26]. This modular testbed allowed us

to isolate and record empirical telemetry degradation profiles across shifting signal-to-noise ratios, which were subsequently converted into stochastic communication latency and packet-loss probability functions to be injected directly into the multi-agent reinforcement learning environment.

The physical-layer characterization of vehicular enclosures introduced unexpected material and measurement challenges. While evaluating high-curvature laminated glass specimens integrated with embedded micro-strip antenna arrays, our early tests assumed uniform dielectric properties across the specimen surface. However, when placing these large-format laminated components into our multi-axis RF chamber under simulated thermal gradients, non-uniform adhesive interlayer curing and localized curvature radii induced substantial variations in signal insertion loss. Calibrating the automated RF receiving sensitivity measurement equipment across these curved surfaces proved exceptionally delicate, requiring continuous recalibration of baseline noise figures. These empirical calibration difficulties compelled us to accept that physical enclosures do not exhibit static electromagnetic transparency; rather, structural tolerances and temperature gradients induce continuous, non-linear radio-frequency attenuation that fluctuates dynamically as vehicles traverse urban environments.

A parallel experimental dilemma arose during the evaluation of edge processing hardware and power stability under sustained computational strain. During initial benchmark runs where edge microcontrollers executed simultaneous multi-sensor fusion and lightweight inference tasks, localized thermal hot spots developed across the battery-compute interface. The internal resistance of the polymer lithium-ion power cells escalated rapidly, generating anomalous sensor readings that our early data filtering scripts misidentified as catastrophic battery failure. To prevent premature thermal shutdowns and maintain signal integrity, the experimental protocol had to be revised to include continuous infrared thermal imaging and synchronized impedance spectroscopy. Simultaneously, managing the massive volume of empirical sensor telemetry across our experimental pipeline required adhering to rigorous technical standards for cross-platform data integration, avoiding format discrepancies that frequently plague enterprise-scale hardware testbeds [16]. These adjustments exposed the fragile operational margins of vehicular edge devices, illustrating that algorithmic processing demands cannot be increased indefinitely without triggering physical safety throttles.

3. Empirical Findings and Hardware-Layer Observations

Synthesizing the empirical observations gathered across our distributed algorithmic simulations and localized hardware stress trials revealed pronounced systemic disruptions when macroscopic dispatch policies collided with physical-layer degradations. In baseline simulated environments operating under ideal communication assumptions, the multi-agent reinforcement learning dispatch framework demonstrated rapid policy convergence, successfully rebalancing simulated vehicle deficits across urban traffic sectors and reducing average passenger waiting times by twenty-eight percent. However, when the empirical hardware-derived telemetry attenuation models—reflecting dynamic V2X receiving sensitivity degradation and enclosure dielectric losses—were enabled within the simulation loop, the global operational metrics exhibited severe, non-linear degradation. Rather than achieving smooth spatial-temporal fleet equilibrium, autonomous agents exhibited recurring coordination delays, localized clustering in peripheral zones, and prolonged dispatch latencies that substantially eroded the theoretical throughput gains.

Analysis of the onboard radio-frequency telemetry performance under simulated environmental aging unmasked the underlying mechanisms driving this algorithmic failure. Data retrieved from our continuous

hardware stress testbeds revealed that vehicular RF power amplifiers experience progressive performance degradation when subjected to sustained electrical stress and thermal cycling. This finding directly corroborates the longitudinal experimental degradation patterns identified by Zhao, wherein automotive-grade RF power amplifiers demonstrate marked output power compression, increased harmonic distortion, and elevated noise figures following extended endurance aging [24]. In our closed-loop tests, this amplifier degradation led to an exponential expansion of communication dead zones, particularly along urban sector boundaries where handovers between roadside infrastructure and adjacent vehicles occur. When dispatch commands were transmitted across these degraded physical channels, the effective packet reception rate plummeted, causing distributed autonomous agents to make local repositioning decisions based on outdated global state observations.

Simultaneously, the physical properties of the laminated enclosure assemblies contributed to significant spatial-temporal variance in telemetry reliability. Our multi-physics benchtop tests indicated that high-curvature glass geometries, while structurally robust, induced anisotropic antenna radiation pattern distortions. At extreme incident angles, the measured signal attenuation exceeded predicted analytical models by up to six decibels, an effect intensified when surface temperatures exceeded forty-five degrees Celsius. This physical attenuation directly degraded the receiving sensitivity of the embedded V2X communication modules. Consequently, vehicles oriented in specific geometric headings relative to road-side units experienced sudden telemetry drops, resulting in fragmented situational awareness. The multi-agent algorithm, lacking any explicit awareness of these orientation-dependent physical constraints, repeatedly penalized agents for execution delays that were actually governed by dielectric and geometric enclosure properties.

At the localized edge computing node, the physical strain of maintaining continuous coordination generated subtle, cascading failure modes. Under heavy algorithmic dispatch traffic, onboard microcontrollers attempting to process lightweight feature extraction and multi-sensor telemetry simultaneously experienced rapid thermal buildup. Rather than maintaining consistent processing throughput, edge nodes exhibited transient clock-frequency throttling to prevent thermal runaway in adjacent lithium-ion cells. These thermal mitigation cycles introduced stochastic computational latencies that varied from fifty milliseconds to several seconds. In several instances, these processing delays prevented vehicles from confirming dispatch assignments within designated time windows, triggering redundant secondary dispatch mandates that destabilized adjacent fleet sectors. The empirical data unmistakably demonstrated that macroscopic algorithmic convergence cannot be sustained when microscopic hardware components operate near their physical, electromagnetic, and thermal boundaries.

4. Critical Discussion, Competing Hypotheses, and Interpretive Biases

Interpreting the divergence between theoretical multi-agent optimization and empirical hardware execution requires exploring competing explanations and identifying potential analytical biases that may distort our understanding of cyber-physical vehicular systems. A prevailing view within modern algorithmic literature contends that multi-agent reinforcement learning possesses inherent robustness to environmental stochasticity, suggesting that communication latency and packet loss can be adequately absorbed as generalized observation noise within partially observable Markov decision processes. However, the non-linear degradation observed in our empirical trials indicates that this assumption is fundamentally flawed. Hardware-induced disruptions do not behave as zero-mean Gaussian perturbations; rather, they manifest as structurally correlated, spatially dependent systemic failures. When multiple autonomous vehicles encounter identical electromagnetic shadowing or thermal constraints within a

specific urban sector, their telemetry degrades concurrently, inducing correlated policy failures that destabilize macroscopic fleet coordination.

Alternative explanations focusing on communication protocol dynamics must also be rigorously evaluated. It is possible that the dispatch failures observed in our testbed were not solely driven by radio-frequency power amplifier degradation or enclosure attenuation, but were exacerbated by MAC-layer contention algorithms within the V2X stack itself. In dense urban sectors, packet collisions and channel congestion inherently increase, creating backoff delays that mimic physical hardware degradation. Differentiating between purely electromagnetic signal loss and upper-layer protocol bottlenecks represents an analytical challenge that current testing methodologies struggle to resolve fully. Furthermore, scaling fleet-wide coordination requires integrating dynamic vehicle states with broader enterprise service platforms, where platform operational efficiency directly impacts real-world resource allocation [23]. In complex multi-stakeholder transportation networks, adopting dynamic marketing automation and operational optimization paths provides vital tools for balancing fluctuating commercial demand with physical fleet capacity [22]. When customer and telemetry streams traverse diverse regional cloud platforms, compliance technologies and secure cross-border transfer protocols become indispensable to prevent catastrophic operational halts [7].

At the physical maintenance level, fleet viability depends heavily on rapid turnaround times for replacement sensors, battery packs, and communication modules, where seamless operational synchronization between resource planning and warehouse inventory systems determines component replacement speed [6]. For regional operators operating under capital constraints, adopting lightweight digital deployment frameworks offers a pragmatic operational path for managing distributed vehicular assets without incurring prohibitive technical overhead [18]. From a macro-infrastructure perspective, autonomous fleet deployment cannot be evaluated in isolation from public capital governance. Roadside computing infrastructure and communication relays represent significant capital commitments, requiring rigorous capital efficiency governance to ensure long-term public infrastructure viability [10]. When infrastructure projects transition into execution, financial vulnerability controls integrating engineering management and rigorous accounting practices are essential to prevent cost leakage [15]. Without structured cost-governance mechanisms, large-scale vehicular infrastructure projects frequently suffer from catastrophic budget overruns [19]. Mitigating these capital misallocations during project delivery requires establishing joint engineering-accounting models to curtail cost-related financial losses [17], while simultaneously enforcing joint review procedures to alleviate principal-agent hazards between municipal agencies and private contractors [20]. To sustain the broader industrial ecosystem, multi-dimensional transmission mechanisms within industrial service platforms are necessary to empower private enterprise integration into smart transportation initiatives [14]. Furthermore, accelerating the real-world translation of these integrated cyber-physical technologies depends fundamentally on the operational mechanics and achievement transformation efficiency of industry-university-research collaborative platforms [13].

These compounding uncertainties compel a foundational reassessment of how connected and autonomous mobility architectures are conceptualized and evaluated. Continuing to optimize macroscopic multi-agent reinforcement learning algorithms in mathematical isolation from the underlying hardware physics represents a dead end for industrial deployment. Algorithmic researchers must acknowledge that physical-layer metrics—such as RF amplifier health, enclosure dielectric transparency, and battery thermal reserves—are not merely secondary engineering constraints to be managed post-hoc, but fundamental operational state variables that directly govern algorithmic feasibility. Unless future

multi-agent models explicitly embed physical-layer degradation indices into their state representations and reward formulations, autonomous fleet systems will remain vulnerable to catastrophic execution failures when transitioning from pristine digital simulations into the uncompromising physical reality of the road.

5. Theoretical Synthesis, Practical Implications, and Forward Perspectives

Considering the complex cross-layer interdependencies and empirical frictions identified throughout this investigation, this leads us to further thinking regarding the theoretical and architectural convergence of distributed algorithmic dispatch and physical-layer automotive engineering. Rather than treating multi-agent reinforcement learning, vehicle-to-everything telematics, and in-vehicle hardware enclosures as isolated technological layers, the future of autonomous shared mobility demands a unified cyber-physical paradigm where macroscopic dispatch policies adapt dynamically to real-time physical-layer health metrics. Integrating predictive telemetry degradation indices, multi-physics enclosure tolerances, and edge thermal safety margins directly into distributed optimization algorithms will allow vehicular fleets to balance transport efficiency against hardware wear and operational risk. Moving forward, the discipline must transcend synthetic software simulations by establishing integrated, multi-domain digital twins capable of modeling electromagnetic wave propagation, structural material aging, and battery thermal dynamics simultaneously alongside spatial fleet logistics. Developing such holistic, cross-layer co-design frameworks will bridge the historical divide between computer science and automotive systems engineering, ultimately elevating autonomous electric mobility from an idealized algorithmic concept into a resilient, industrially viable urban reality.

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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