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Short Communication

Embodied Intelligence at Scale: Cross-Platform Transfer and Large-Scale Sensing in Autonomous Mobility

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1 Introduction

The rapid advancement of embodied intelligence is reshaping how physical AI systems acquire and generalize knowledge. Foundation models capable of transferring learned behaviors across morphologically distinct platforms—from wheeled vehicles to legged robots to aerial drones—have emerged as a unifying paradigm. Autonomous vehicles represent a particularly consequential application domain for this technology, given their scale of deployment and the complexity of urban environments they must navigate. Simultaneously, the global proliferation of sensor-equipped autonomous vehicles creates unprecedented opportunities for large-scale environmental monitoring. These developments demand attention from the transportation research community regarding both the scientific opportunities they present and the governance frameworks they require.

2 The Convergence of Physical Intelligence

The traditional boundaries separating autonomous vehicles, mobile robots, and unmanned aerial systems are dissolving under the pressure of unified foundation models. Recent developments demonstrate that perception-action architectures trained in one domain can transfer effectively to others, challenging the long-held assumption that physical intelligence requires platform-specific training from scratch.

This convergence is underpinned by a fundamental insight: reward maximization, the principle underlying both biological organisms and artificial learning systems, can support the acquisition of transferable physical intelligence (Lu et al., 2025). The bilevel optimization framework introduced by Lu et al. addresses a critical bottleneck in embodied reinforcement learning---the discovery of optimal reward functions without extensive task-specific engineering. Their approach demonstrates that reward functions can be automatically discovered through regret minimization, enabling policy transfer across diverse tasks while accelerating convergence. The implications extend beyond computational efficiency; the work suggests that shared cognitive primitives may underlie physical intelligence across morphologically distinct systems, analogous to convergent evolution in biological organisms.

The challenge of transferring learned intelligence across different urban contexts presents additional complexity. Cross-city transfer learning has emerged as a critical methodology for scaling smart mobility solutions, yet significant barriers remain---including heterogeneous data distributions, varying infrastructure configurations, and distinct regulatory environments. Understanding these transfer challenges is essential for deploying embodied AI systems that can generalize across diverse urban environments without requiring complete retraining for each new context. A complementary and arguably the most active transfer paradigm is sim-to-real transfer---translating policies trained in high-fidelity simulation into robust real-world performance. Advances in domain randomization, photorealistic scene synthesis via Neural Radiance Fields and Gaussian Splatting, and large-scale World Foundation Models have substantially narrowed the simulation-to-reality gap; yet unmodelled dynamics, sensor noise, and adverse weather continue to challenge transfer fidelity, making adaptive real-to-sim-to-real pipelines an open frontier with direct implications for safe autonomous mobility deployment.

The challenge of scaling embodied AI extends beyond individual agents to the complex interactions that emerge when multiple autonomous systems share physical space. Higher-order interactions in networked systems produce dynamics that differ fundamentally from pairwise relationships (Zhang et al., 2023). As fleets of autonomous vehicles, delivery robots, and aerial drones increasingly cohabit urban environments, understanding these higher-order dynamics becomes essential for predicting emergent behaviors and ensuring system stability. The choice of mathematical representation---whether hypergraphs or simplicial complexes---profoundly influences conclusions about collective dynamics, a finding with direct implications for modeling cooperative autonomous systems.

3 Autonomous Vehicles as Large-Scale Sensor Networks

Beyond their transportation function, autonomous vehicles constitute what may become the largest mobile sensor network in human history. Each vehicle continuously captures atmospheric

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conditions, visual imagery, road surface states, and acoustic signatures at unprecedented spatial and temporal resolution. This data infrastructure presents transformative opportunities for environmental science — from real-time air quality mapping at fine spatial resolution to biodiversity monitoring through roadkill surveys and wildlife corridor detection.

The scientific potential remains largely unrealized due to fundamental governance gaps. Corporate data silos prevent scientific access to observations that could advance urban climatology, public health research, and ecological monitoring. The absence of standardized data taxonomies impedes cross-platform integration, while privacy considerations remain unresolved. Unlike meteorological data, which benefits from international sharing agreements established over decades, mobility data lacks comparable frameworks for scientific access.

The imperative for climate-neutral urban mobility adds urgency to these considerations. Multi-city empirical evidence from European shared e-scooter systems reveals complex carbon emission patterns that challenge simplistic assumptions about micromobility sustainability (Yang et al., 2026). Understanding these patterns requires precisely the kind of cross-platform, cross-city data integration that current governance gaps impede. As autonomous systems increasingly integrate with shared mobility ecosystems, the environmental monitoring capabilities of vehicle sensor networks become essential for validating climate benefits and identifying unintended consequences.

4 Critical Tensions Requiring Scientific Input

The reward function problem extends beyond technical optimization to fundamental questions of values and governance. Whose preferences should inform the objectives that autonomous systems optimize? The framework of regret minimization provides mathematical elegance, but the definition of regret necessarily embeds normative assumptions about desired outcomes. In heterogeneous urban environments where pedestrians, cyclists, and vehicles share space, trajectory planning requires ethical frameworks that remain contested and culturally variable.

Data sovereignty presents another dimension of tension. As of July 2025, Waymo had surpassed 100 million fully autonomous miles[1] — scientifically invaluable data that remains proprietary. Meanwhile, open-source initiatives, particularly from Chinese manufacturers and research consortia, offer alternative models for data access. The scientific community could advocate for "scientific access zones" within mobility data, analogous to agreements governing satellite imagery, that preserve privacy while enabling research.

The safety-capability frontier poses perhaps the most significant challenge. Demonstrably safe AI requires verification methods that do not yet exist for systems that learn and adapt in deployment (Li et al., 2025), and World models enable prediction but introduce new failure modes — hallucination in physical space carries consequences fundamentally different from errors in text generation. Champion-level performance in constrained domains such as drone

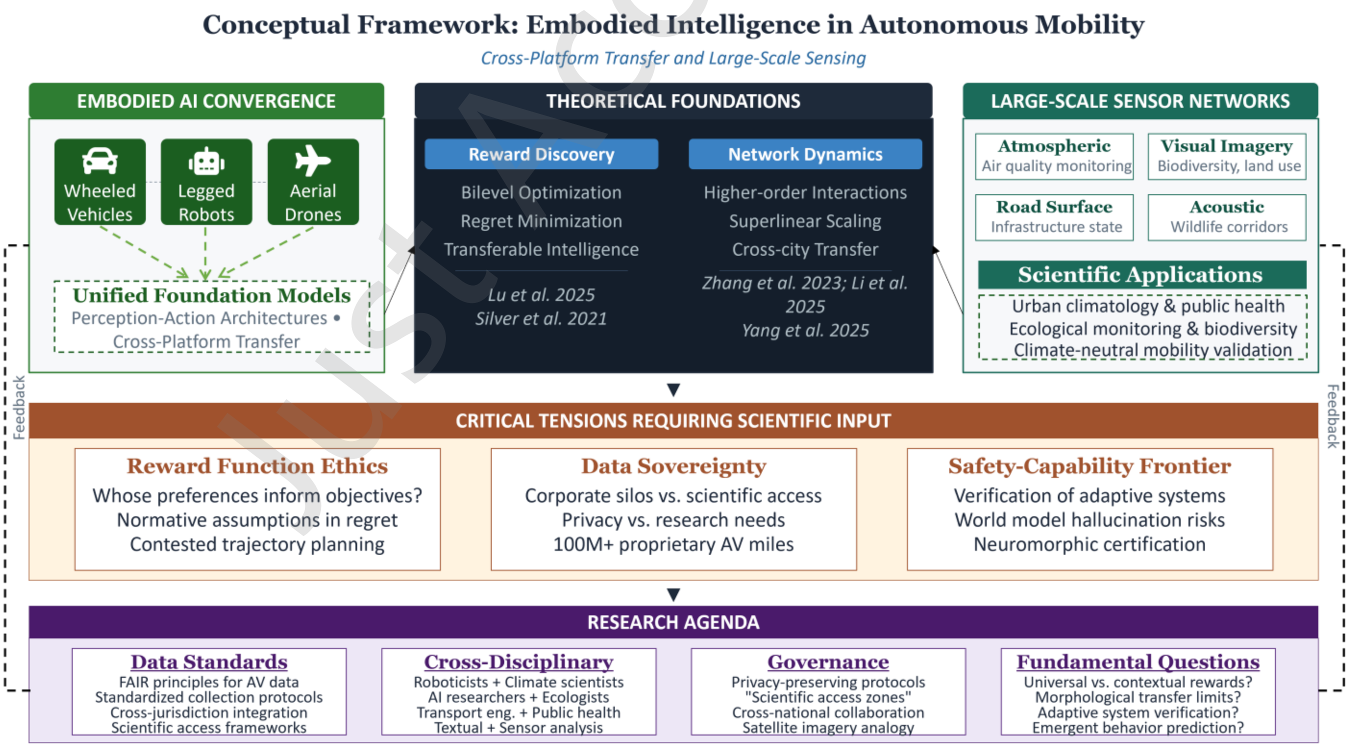

Fig. 1. Conceptual framework for embodied intelligence in autonomous mobility. The framework illustrates the convergence of: (a) Embodied AI Convergence — the unification of autonomous vehicles, mobile robots, and aerial systems through foundation models enabling cross-platform transfer; (b) Large-Scale Sensor Networks — the scientific opportunities arising from autonomous vehicle fleets as extensive environmental monitoring infrastructure; and (c) Theoretical Foundations — including reward discovery through bilevel optimization (Lu et al., 2025) and higher-order network dynamics (Zhang et al., 2023). These developments generate critical tensions around reward function ethics, data sovereignty, and safety verification, informing a research agenda spanning data standards, cross-disciplinary collaboration, governance frameworks, and fundamental scientific questions.

[1] Waymo Safety Hub, December 2025. https://waymo.com/safety/impact/ — scientifically invaluable data that remains proprietary.

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racing demonstrates remarkable capabilities (Kaufmann et al., 2023), yet the transfer of such achievements to open-world urban environments remains an unsolved challenge. Operational safety platforms for unmanned aircraft systems in critical urban areas represent an emerging infrastructure layer that must accompany capability advances (De Luca et al., 2025).

5 Toward a Research Agenda

The research community faces a narrow window to shape how embodied AI develops within transportation systems. Unlike digital AI operating in controlled server environments, embodied AI will inhabit streets, homes, and workplaces, making governance decisions consequential for decades.

Immediate priorities include standardization of environmental data collection protocols comparable to FAIR (Findable, Accessible, Interoperable, Reusable) data principles, ensuring that observations from autonomous vehicles can support reproducible research across jurisdictions. Cross-disciplinary collaboration must bridge currently fragmented communities: roboticists and climate scientists, AI researchers and ecologists, transportation engineers and public health researchers. Governance frameworks must balance scientific access with privacy protection while enabling cross-national research collaboration essential for addressing global challenges.

Fundamental research questions remain open. Can reward functions be universally discovered, or do they remain irreducibly context-dependent? What are the physical limits of transferable embodied intelligence — do morphological differences impose fundamental constraints on policy transfer? How can safety be verified in systems designed to learn and adapt, whose behavior by definition cannot be exhaustively specified in advance?

The decisions made in the coming years about data governance, safety verification, and cross-platform intelligence will determine whether embodied AI serves broad scientific and social goals or remains fragmented across corporate silos and national boundaries. The transportation research community is well positioned to define standards for embodied AI safety, advocate for scientific data access frameworks, and bridge the disciplinary divides that currently impede progress. The convergence of physical AI across platforms, combined with the large-scale sensing capability of autonomous vehicle fleets, represents an opportunity that merits sustained research attention.

Author contributions

Yiping Yan: Writing – original draft, Investigation, Methodology. **Ying Yang:** Writing – review & editing, Supervision, Conceptualization, Formal analysis, Investigation, Methodology, Funding acquisition. **Inhi Kim:** Writing – review & editing, Supervision, Conceptualization, Formal analysis, Investigation, Methodology.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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