Research Statement

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Table 1: Summary of Research Impact (as of Sep 22, 2025)

Research Funding	58 projects: PI on 38 totaling \$24.0M (VU share: \$10.9M) and Co-PI on 20 totaling \$45.1M; At Tenure: 39 projects with PI on 22 totaling \$8.3M (VU share: \$4.9M) and Co-PI on 17 totaling \$27.6M.
Scholarship	253 refereed publications; 51 journal papers; 63 highly selective conference papers (acceptance rate <33%); H-index 39; 5668 citations. Recent highly selective publications include: NeurIPS 2025 (NS-Gym, ESCORT) [11, 2], ICLR 2025 and AAMAS 2024 (Decision Making Under Uncertainty and Non-stationarity) [20, 5], ICAPS 2025 (POMDP belief updates), ICCPS 2025 and AAMAS 2025 (Vehicle to Building Adaptive Planner) [8, 4], ICCPS 2024 (Online Decision Making For Transit Vehicles) [26], AAMAS 2025 and ECAI 2024 (explainable CPS planning) [14, 1] . At Tenure: 172 refereed publications; 33 journal papers; 19 highly selective conference papers; H-index 27; 2564 citations.
Students	PhD Graduated: 6; MS Graduated: 3. Current PhD Advisees: 10 across CS and EE; Current postdocs/research scientists: 4; Past postdocs: 4. At Tenure: PhD Graduated: 3; MS Graduated: 2;
Awards	NSF CAREER (2022); Best Paper Awards: ICCPS 2024, IJCAI 2022, SmartComp 2019, ICAS 2012; Equity in Transportation Award at INFORMS 2024; Multiple Best Paper Finalists (AAMAS 2025, SmartComp 2025).
Recognition	Vanderbilt Chancellor Faculty Fellow (2024–26), Community Impact Research Award (2025), Catalyst Innovation Award (2023), Google Cloud Research Champion (2023–25).
Patents	Energy-aware mixed-fleet forecasting (2023); EV charging control devices (2024); Dynamic vehicle routing (2024).
Software	ARINC 653 emulator [116]; CHARIOT [77]; DeepNNCar [60]; ReSonAte [45]; TRANSAX [44]; Anti-CARLA [37]; Smart Transit [21]; Statresp [53]; RIAPS [83]; MODICUM [51, 32]; DREMS [106]; OPTIMUS [27].
Startups	Co-founder and CSO of Mobius AI (2023–), delivering SaaS for fleet management and energy-aware routing.
Impact	Operational solutions for CARTA, WeGo, Nissan, Siemens, TDOT, and Nashville Fire Department (paratransit optimization, predictive school bus routing, fire station planning).
Leadership	General Chair, ICCPS 2024; Steering Committee, ICCPS (2025–); Program Co-Chair (ICCPS 2023, ICAA 2023); Director of SCOPE Lab (2016–); NSF CISE CNS Program Director Co-leading CPS, S&CC and CIVIC programs.

1. Overview

Societal-scale cyber-physical systems (CPS)—such as transportation networks, electric power grids, and emergency response infrastructures—form the backbone of modern life. Yet these infrastructures are increasingly strained by rapid urbanization, aging assets, shifting patterns of demand, and resilience concerns. Traditional optimization and rule-based control approaches, while effective in well-structured and static environments, often are found lacking when facing uncertainty. Generative AI approaches, while transformational for language and images, are unable to help with non-myopic decision making. This includes planning, scheduling, and combinatorial optimization, alongside rigorous approaches for failure detection, monitoring, interpretability, adaptability to non-stationarity, and risk-aware reasoning.

My research is directed toward addressing this challenge, focusing on decision procedures that can scale to real-world complexity while maintaining the transparency and trustworthiness essential for societal adoption. Since 2016, this vision has been realized through my research lab at Vanderbilt University, the SCOPE Lab.

Our work has led to advances in neurosymbolic and assured decision-making, theoretical foundations for non-myopic planning under uncertainty, and machine learning models for anomaly detection and monitoring in real-world CPS. These contributions have been recognized with best paper awards and finalist nominations at ICCPS, AAMAS, INFORMS, and IJCAI, as well as faculty honors including the Vanderbilt Chancellor Faculty Fellowship and the Community Impact Research Award. At the same time, our emphasis on real-world validation

Table 2: Students Mentored in Past (as of Sep 22, 2025)

Michael Wilbur [Ph.D. 2023]	Data-Driven Algorithms for Smart Transportation Systems (energy-aware transit optimization, forecasting). Now CTO of Mobius AI.
Ava Pettet [Ph.D. 2022]	Principled Algorithms for Real-time Sequential Decision Making for Large-Scale CPS (decision-making under uncertainty).
Shreyas Ramakrishna [Ph.D. 2022]	Dynamic Safety Assurance of Autonomous CPS (safety monitoring, assurance frameworks).
Scott Eisele [Ph.D. 2020]	Resolving Challenges in Multi-Stakeholder CPS Using Distributed Ledgers (blockchain for resilience).
Fangzhou Sun [Ph.D. 2018]	Co-Mentored with Prof. Jules White. Algorithms for Context-Sensitive Prediction, Optimization and Anomaly Detection in Urban Mobility.
Subhav Pradhan [Ph.D. 2017]	Co-Mentored with Prof. Aniruddha Gokhale. Algorithms and Techniques for Managing Extensibility in Cyber-Physical Systems (modularity and extensibility middleware).
Matthew Buruss [M.S. 2020]	Enhancing the Robustness of Deep Neural Networks Against Security Threats Using Radial Basis Functions.
Sanchita Basak [M.S. 2020]	Spatiotemporal Anomaly Detection and Prediction of Anomaly Propagation Path Using LSTM Networks
Chinmaya Samal [M.S. 2019]	Time-dependent and Privacy-Preserving Decentralized Routing using Federated Learning.
Jose Paolo Talusan [Postdoc]	Mentored in AI decision making for CPS; now working as a research scientist with us.
Ava Pettet [Postdoc]	Mentored in resilience and decision-making; now advancing independent career.
Saideep Nannapaneni [Postdoc]	Mentored in AI safety and manufacturing CPS; now advancing independent career.

has led to multiple patent applications and successful deployments in partnership with community organizations as well as industry partners, including WeGo, Metro Nashville Information Technology Services (ITS), Nashville Fire Department (NFD), Chattanooga Area Regional Transportation Authority (CARTA), Nissan, Siemens, Cisco, the Tennessee Department of Transportation (TDOT), and the Nashville Department of Transportation (NDOT). These collaborations have enabled us to deliver production-ready solutions: from optimizing paratransit operations in Chattanooga and predictive school bus routing in Williamson County, to integrating EV fleets with the electric grid, improving fire station planning in Nashville, and advancing resilience in public transit. A summary of key research impacts is shown in the table 1. This work has been supported through partnership with several graduate students over my career (see Table 2).

Building on this foundation, we launched Mobius AI, a translational venture that operationalizes our research in AI-driven fleet management and energy-aware routing. The platform delivers *software-as-a-service solutions* for paratransit, microtransit, and mixed fleets, enabling agencies to reduce operational costs, improve service reliability, and accelerate the adoption of electric vehicles. Early deployments with partners demonstrate how our scientific contributions scale into transformative societal impact. Rest of this statement provides further description across two synergistic thrusts: (1) *Foundational contributions to CPS science*, with a focus on AI-driven decision-making, anomaly detection, and resilience; and (2) *Use-inspired research for mobility and energy domains*, where these principles are deployed at scale in collaboration with transportation agencies, utilities, and industry partners.

2. Foundational Contributions to Cyber Physical System Science

Decision-making problems in societal-scale CPS are often computationally intractable at scale, their operating environments are inherently non-stationary, and the "black-box" nature of many AI algorithms creates a significant barrier to trust and adoption. Compounding these issues is the critical necessity for resilience. Addressing these challenges requires not only robust algorithms but also a new generation of platforms capable of implementing these advanced capabilities at the network edge, where low-latency decision-making is paramount. My research program has made fundamental contributions to this science through a multi-pronged approach focused on AI-driven decision-making, anomaly detection, and resilience, supported by the development of robust platforms.

2.1 **AI Policies for Decision Procedures**: A central thrust of this work, and the focus of my NSF CAREER Award, is the development of foundational methods for AI-driven decision-making in societal-scale CPS. To address scalability, we first developed hierarchical planning frameworks that decompose massive Markov Decision Processes (MDPs) into tractable sub-problems, a technique applied successfully to city-scale emergency response [36]. We then pioneered non-myopic decision-making algorithms that integrate offline policies with online search, leading to "Decision Making in Non-Stationary Environments with Policy-Augmented Monte Carlo Tree Search" [35], which accelerates search by leveraging policies as structured heuristics. Subsequently, in the "Act as You Learn: Adaptive Decision-Making in Non-Stationary Markov Decision Processes" paper we proposed Adaptive MCTS (ADA-MCTS) [20], disentangling epistemic and aleatoric uncertainty to enable robust adaptation. "Dynamic Simplex: Balancing Safety and Performance in Autonomous Cyber Physical Systems" [30] showed how to maintain safety while switching between policies. We also released NS-Gym [2], the first open-source toolkit for reinforcement learning in non-stationary MDPs. Most recently, "Decision Making in Non-Stationary Environments with Policy-Augmented Search" generalized the PA-MCTS framework [23], while "Scalable Decision-Making In Stochastic Environments Through Learned Temporal Abstraction" demonstrated how temporal abstraction accelerates adaptation in high-dimensional spaces [5]. We extended these techniques to domain-specific challenges, such as long-horizon energy scheduling in "Reinforcement Learning-based Approach for Vehicle-to-Building Charging with Heterogeneous Agents and Long Term Rewards" [4], and to partially observable environments for CPS in "Observation Adaptation via Annealed Importance Resampling for POMDPs" [10]. Alongside performance and robustness, explainability has been a consistent theme. "Enabling MCTS Explainability for Sequential Planning Through Computation Tree Logic" [14] and "Combining LLMs with a Logic-Based Framework to Explain MCTS" [1] showed how neurosymbolic and language-based methods generate human-readable explanations with formal guarantees for online search based decisions procedures. Together, these works provide a scientific foundation for adaptive, interpretable, and domain-integrated decision-making in CPS, bridging efficiency, robustness, and transparency.

2.2 **Platforms and Middleware for Resilient CPS**: My early work focused on creating platforms to ensure resilience in complex, real-time systems. This began with component-based models that enforce strong isolation, such as the ARINC-653 Component Model (ACM) [116], which combines spatial and temporal partitioning with component-level monitoring of pre- and post-conditions on method invocations, state invariants, resource usage, and timing behavior. This work was extended to distributed systems with the DREMS (Distributed Real-Time Embedded Managed Systems) component model [80, 95, 100, 98, 106, 109], which featured fine-grained privileges and a novel Multi-Level Security (MLS) information sharing policy [100, 103, 104, 109]. A parallel thrust developed methods for performance prediction and capacity planning [58, 97, 99, 101, 114, 120, 121, 118, 119, 123, 126, 127, 124], including adaptive management under degraded scenarios [61, 80, 108, 122] and uncertainty [76, 87, 91, 90, 102]. Subsequently, we focused on network's edge in CPS. A key contribution is the Resilient Information Architecture Platform for Smart Systems (RIAPS), a decentralized, fault-tolerant middleware now part of the Linux Foundation [74, 85, 62, 83, 82, 79]. RIAPS enables secure, peer-to-peer applications and underpins our transactive energy platform, TRANSAX, which uses a hybrid solver pattern [74, 73, 75] and verifiable smart contracts [50, 63, 64] to create a safe and private energy market [44, 49, 52]. This work also led to MODICUM, a middleware for spot computation markets at the edge [51], enabling deployment of AI policies, and frameworks for the scalable testing of IoT applications [68, 89]. In addition to middleware platforms, a key requirement is efficient simulation models for training as well as run-time inference. To address this, we developed open-source platforms including NS-Gym for non-stationary RL environments [2], Power-Attack for cyber-attack simulation in power grids [43], E-Transit Bench for electric mobility simulation [38], and OPTIMUS for vehicle-to-building charging optimization [27]. Together, these tools integrate system behavior into both training and operational decision-making.

2.3 **Fault Isolation and Anomaly Detection**: My work in this area has shown that if a CPS is constructed using a component-based design, the behavior and failure propagation across the assembly can be deduced [107, 105, 113, 108, 111, 110, 112, 117, 115]. A challenge, however, is that system topologies change over time, introducing new failure modes specific to the operation or lack of operation of the protection components.

We developed an extension of Temporal Failure Propagation Graphs called Temporal Causal Diagrams (TCD) to resolve these challenges by augmenting the model with the behavior of local observers and fault masking patterns [71]. For anomaly detection, my work has shown that when data can be collected from spatial neighborhoods, the variance from the collective group and time-dependence can be used to detect anomalies. An early statistical approach using Pythagorean mean-based metrics [69] was sensitive to neighborhood size, but we found that adding domain knowledge, such as modeling road interactions [59, 57] or using graph neural networks to capture network structure [33], significantly improves performance. For high-dimensional data, our work has shown that latent representations from variational autoencoders can detect problems, especially for AI components where the runtime data distribution may differ from the original training distributions [47, 56]. Further, we have developed techniques using conditional normalizing flows [28, 12] to not only identify anomalies efficiently at scale when testing labels are not present, but also synthesize training sets that can be used to train more efficient classifiers eventually.

2.4 **Resilience and Recovery** Once a fault is isolated, recovery is critical. My work has advanced beyond prescriptive, rule-based strategies [125, 61] to planning-based Software Health Management and deliberative runtime reconfiguration. The key idea was to use the design space of the CPS—encoding resources, faults, and goals using domain-specific languages [81, 95, 96] developed for the System-F6 and CHARIOT projects—to search for alternatives when faults occur [77, 94, 93]. To manage risk at runtime, we introduced the ReSonAte dynamic risk estimation framework, which reasons over Bow-Tie Diagrams capturing hazard propagation paths [45]. For recovery, we used a dynamic simplex strategy to transition to a safe controller by creating a weighted ensemble of the two control outputs, balancing safety and performance [55, 66, 30].

3. Use-Inspired Research for Mobility and Energy Systems

My research program leans heavily on use-inspired aspects, driven by the conviction that scientific advances must be validated against the complexities of real-world operational environments. This philosophy is most evident in our sustained, collaborative work within the critical, and interconnected, domains of intelligent mobility and resilient energy systems. By partnering directly with public transit agencies, city and state departments of transportation, utilities, and industry leaders, we ensure that our work is grounded in pressing operational needs. This approach creates a powerful feedback loop where practical challenges motivate foundational inquiry, and theoretical breakthroughs enable robust, deployable solutions that have a measurable impact on community well-being, efficiency, and resilience. This section details these translational efforts in each of the domains.

3.1 **Emergency Response**: My research in mobility is defined by sustained partnerships with public agencies to solve high-stakes operational problems, moving from predictive analytics to proactive, AI-driven optimization. Our work with the Nashville Fire Department began with predictive analytics to understand incident patterns [88, 86, 65], which revealed the limitations of reactive models and motivated a shift toward proactive resource allocation. This directly intersected with our foundational science on scalable planning, leading to a hierarchical planning framework that decomposes the city-scale emergency response problem into tractable sub-problems, significantly improving response times in validation with real-world data [36]. Building on this, we introduced proactive spatio-temporal stationing and dispatch algorithms [46], which demonstrated substantial gains in reducing urban emergency response times. These advances were further supported by uncertainty modeling using Uncertain Concept Graphs (UCGs) to represent incomplete or conflicting information in dispatch operations [78], improving robustness under noisy incident reports. To extend scalability and adaptivity, we developed multi-agent decision-support systems based on decentralized Monte Carlo tree search [54], enabling distributed yet coordinated response planning. Most recently, this line of work has advanced to multi-agent reinforcement learning for stationing and dispatching ambulances to incident, which reduces decision time substantially while preserving robustness [25]. This ongoing collaboration was recently accelerated by a Nashville Innovation Alliance grant to create actionable and accessible tools for NFD's strategic planning [6]. Together, these contributions establish a pipeline from predictive analytics to explainable, adaptive, and scalable emergency response optimization in partnership with public safety agencies.

3.2 **Mobility Systems**: A similar trajectory unfolded in public mobility systems, evolving from predictive analytics to creating end-to-end optimization solutions. Early collaborations with Nashville WeGo focused on delay prediction [67] and managing service during the COVID-19 pandemic, which led to a data-driven analysis of its impact on ridership and accessibility [31]. Our work with the Chattanooga Area Regional Transportation Authority (CARTA) has been particularly impactful, beginning with foundational data-driven models for energy forecasting across their mixed fleet of electric and internal combustion vehicles under the DOE HD-EMMA grant [42, 48]. This energy-aware perspective informed a suite of novel algorithms for microtransit and paratransit, including offline routing that integrates mandatory driver breaks [3], methods for handling offline VRP (Vehicle Routing Problems) with online bookings [40], rolling horizon temporal decomposition for scalability [29], and online MCTS-based planners for dynamic, stochastic trip requests [41]. This research culminated in the deployed *SmartTransit.ai* platform [22, 21], an AI-driven system that, in pilot testing, showed improved efficiency and an increased number of shared rides [18]. The core optimization logic proved highly generalizable, forming the parallel basis for the ADVISER framework, which won the IJCAI 2022 AI for Social Good Best Paper Award for optimizing vaccination resource distribution in Nigeria [34]. For fixed-route transit, we addressed the critical challenge of service disruptions. This work is a direct application of our foundational research in non-myopic planning, resulting in best paper award for "An Online Approach to Solving Public Transit Stationing and Dispatch Problem", an online decision solver that proactively stations and dispatches reserve buses to mitigate disruptions. Validated with data from WeGo, this approach serves more passengers while reducing inefficient "deadhead" miles [26, 9]. This real-world impact has been highlighted in outlets like *WPLN News* and *GovTech*, showcasing how our AI-driven solutions are making transit more efficient and accessible [13, 16]. This body of work has laid the groundwork for major new initiatives. We are now leading the PATH-TN (Partnership for AI-driven Multimodal Transportation Services Integration in Tennessee Cities) project, a \$8.6M USDOT-funded consortium to integrate fixed-route buses, microtransit, and park-and-ride facilities across Tennessee's four largest cities [17]. Further, a new \$3.3M DOE grant with CARTA, titled "AI-Powered Autonomy-Aware Neighborhood Mobility Zones," is focusing on redesigning fixed-line services and integrating them with on-demand autonomous vehicles to increase transit usage and improve energy efficiency[15].

3.3 **Energy Systems**: My research in the energy domain, addresses the dual challenges of decentralization and resilience, with a strong emphasis on the increasingly intertwined nature of energy and mobility systems. Our foundational work began with diagnostics and resilience for the power grid itself. We developed novel formalisms like Temporal Causal Diagrams (TCD) to model and diagnose complex fault propagation in power systems with protection assemblies [71, 72], and created advanced data-driven techniques for anomaly detection, such as using unsupervised Wavelet Convolutional Autoencoders to detect events in high-frequency synchrophasor data [28]. To enable the study of these phenomena, we also developed the Power-Attack toolchain for modeling and simulating cyber-attacks in power systems [43]. Recognizing the need for secure, peer-to-peer energy markets at the grid edge, we developed TRANSAX, which uses a blockchain-based forward-trading market to allow prosumers to manage local resources while solving the conflicting requirements of grid safety, market efficiency, and participant privacy [44, 50, 63, 70, 74, 73, 75, 82, 85, 79, 89, 84, 92]. It enables participants to trade in an energy futures market, which improves efficiency by finding possible matches for energy trades, thereby reducing the load on the distribution system operator. It provides privacy to participants by anonymizing their trading activity using a distributed mixing service while also enforcing constraints that limit trading activity based on safety requirements, such as keeping power flow below line capacity. One of the critical innovations in TRANSAX was developing a novel hybrid solver concept that combines the trustworthiness of distributed ledgers with the efficiency of conventional computational platforms. This work was built upon our foundational research on the RIAPS decentralized middleware platform [62]. Recently, we have also worked on grid resilience against extreme events. We developed a proactive control framework that uses reinforcement learning to intelligently reconfigure the power grid in anticipation of a wildfire's path [19].

3.4 **Combined Mobility and Energy Systems**: A major thrust after I received tenure has been the integration of the mobility and energy domains, focusing on the complex optimization problems that arise as transportation electrifies. This work began with foundational data-driven energy forecasting models for mixed fleets of electric and internal combustion vehicles, developed in partnership with CARTA under the DOE HD-EMMA grant [42, 48]. These predictive models provided the necessary groundwork for operational optimization. Building

Table 3: Current PhD Students and Postdocs (as of Sep 22, 2025)

Sophie Pavia	Dynamic decision procedures for public transit system
Rishav Sen	Resilient Optimization of Mobility Energy Systems
Yunuo Zhang	Decision Procedures for Partially Observable Complex Systems
Baiting Luo	Scalable Neuro-symbolic Decision Procedures for Non-stationary environments.
Jacob Bucklew	Neuro Symbolic Planning and Optimization for Large Combinatorial CPS Problems.
Agrimma Khanna	Dynamic Decision Procedures for Multimodal Microtransit
Ammar Zulqarnain	Planning and Digital Twins for Emergency Response.
Samir Gupta	Dynamic Decision Procedures for Real-time Autonomous CPS
Vakul Nath	Human AI Teaming for Disruption Management for School Buses.

on this, we tackled the challenge of grid-aware operational planning. Our work on optimizing mixed-fleet public transit accounts for dynamic electricity pricing, jointly optimizing charging schedules and trip assignments to minimize costs while respecting vehicle and grid constraints [24]. The most significant integration challenge we have addressed is the Vehicle-to-Building (V2B) problem. We first developed an online decision-making framework using Monte Carlo Tree Search to optimize EV fleet charging under uncertainty, formulating the problem as a Markov Decision Process to handle the large state and action spaces [8]. To improve real-time responsiveness, we created a reinforcement learning-based approach capable of handling heterogeneous agents and optimizing for sparse, long-term rewards like monthly demand charges, using a novel combination of Deep Deterministic Policy Gradient (DDPG) with action masking and MILP-driven policy guidance [4]. This entire research effort is supported by high-fidelity simulation platforms we created to enable the training and validation of these complex control policies. This includes BTE-Sim, a fast simulation environment for public transportation [39], which evolved into E-Transit-Bench for analyzing electric bus fleet operations, and most recently, OPTIMUS, a dedicated discrete event simulator for the V2B challenge [27].

4. Future Research Outlook

Looking forward, my research agenda will continue to be shaped by the pressing need to design and deploy decision-making frameworks that not only achieve efficiency and resilience in societal-scale CPS, but also guarantee assurance, robustness, and human trust at scale. This agenda is supported by my current graduate students collaborating with me on various topics (see Table 3). On the foundational side, my research will advance the science of decision-making under uncertainty and non-stationarity, with a focus on designing assured and robust online planning algorithms at scale. This agenda will extend the principles established in our work on Policy-Augmented Monte Carlo Tree Search (PA-MCTS) [35] and Adaptive MCTS (ADA-MCTS) [20] into a unified framework for Augmented Search, expanding along three synergistic axes: (i) *Policy-Augmented Search*, where we generalize the use of learned policies—even when stale or imperfect—as powerful heuristics to guide online planners and prune intractable search spaces, including Partially Observable Markov Decision Processes (POMDPs) [35, 5, 10]; (ii) *Value-Augmented Search*, which directly integrates learned value functions or domain-specific cost and reward estimators into the Online Search techniques to address sparse or long-horizon rewards—such as the monthly peak demand charges in Vehicle-to-Building optimization [4]—thereby making search fundamentally more non-myopic and efficient; and (iii) *Human-Augmented Search*, where we develop interactive protocols that allow human operators to inject constraints, critique partial plans, or adjust reward functions during the search process, moving beyond passive oversight to active, real-time guidance and embedding explainability and human-AI teaming directly into these decision frameworks.

Building on our work in neurosymbolic explainability for MCTS [14, 1], future research will also extend these ideas into dynamic, dialogue-driven systems in which operators can pose contrastive and counterfactual queries that trigger new, constrained MCTS rollouts, enabling exploration of the consequences of alternative actions in a formally verifiable manner—especially critical in emergency response and public mobility services, where algorithmic choices must be transparent, defensible, and adaptable to shifting contexts.

On the use-inspired side, I will continue focusing on the integration of mobility and energy sector, with an eye for next set of challenges, especially as we begin to integrate autonomous vehicles for public mobility operations. Building on our deployments with WeGo and CARTA, and extending through major new initiatives like the $8.6M USDOT-funded PATH-TN project [17] and the $3.3M DOE-funded work on neighborhood mobility zones [15], we are developing integrated optimization frameworks that jointly coordinate fixed-route transit, paratransit, microtransit, and emerging autonomous vehicle services. A key technical challenge is managing the operational constraints of mixed-autonomy fleets. Our research will advance the AVATAR framework [7], moving beyond traditional time- or distance-based routing to create multi-objective, reliability-aware routing engines. These engines will optimize for metrics critical to autonomous operations, such as route predictability and safety, enabling the seamless integration of AVs into complex, multimodal urban networks.

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