AI Augmented Urban Resilience Agents with Model-Based Behavioral Priors and Theory-Driven Adaptation for Urban Disasters

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Abstract: Disasters cause significant human, economic, and infrastructural losses, disrupting not only essential systems but also the behavioral and spatial routines that sustain urban life, such as how people move, access resources, and make protective decisions. Understanding these human dynamics is essential for emergency management and urban resilience, as individuals' responses depend on both what they are doing and where they are when disruptions occur. Existing approaches capture only fragments of this complexity: surveys and interviews reveal motivations but are retrospective and event-specific, while simulation models, though predictive, rely on fixed behavioral rules that cannot represent adaptive reasoning under unprecedented or compounding hazards. To fill these gaps, this project develops AI-Augmented Urban Resilience Agents (AURA), a new framework that integrates reasoning-capable large language models (LLMs) with empirical behavioral data and psychological theory to simulate how people perceive, reason, and adapt during disasters. By combining data-driven and model-based situational realism with theory-guided behavioral coherence, AURA achieves both realism and generalizability, enabling interpretable simulations that extend across diverse disaster types and urban environments, thereby advancing next-generation urban emergency planning, risk communication, and resilience assessment. Specifically, three interconnected tasks will be conducted. Task 1 builds empirically grounded behavioral baselines using American Time Use Survey (ATUS) data to model typical daily activity transitions by demographic group. Demographic-specific Markov models describe probabilistic daily routines such as working, commuting, and shopping. These patterns are incorporated into each LLM agent's state memory and prompt conditioning to constrain its reasoning within realistic temporal behaviors. A model-based decoding process further ensures that the LLM generated activities remain coherent with the statistical structure of the behavioral model. Task 2 embeds these ATUS-informed agents within real urban environments through activity–location mapping using OpenStreetMap (OSM) and SafeGraph Points of Interest (POI) data. Together with demographic distributions from the American Community Survey (ACS), this spatial embedding provides agents with realistic accessibility constraints, neighborhood heterogeneity, and infrastructure interdependencies that shape feasible decision pathways. Task 3 introduces a Theory-Driven Normal-to-Disaster Transition Module, integrating the Extended Protection Motivation Theory (E-PMT) and the Protective Action Decision Model (PADM) into each agent's reasoning cycle to generate psychologically consistent adaptations to evolving risks such as heat, power loss, or infrastructure failure, conditioned on both the activity context (Task 1) and spatial context (Task 2). The framework will be validated using the 2025 Philadelphia heatwave–blackout, assessing both behavioral realism and predictive performance through meteorological, outage, mobility,

and survey datasets that have been collected or secured through established data-sharing agreement. The interdisciplinary team brings complementary expertise in urban resilience modeling, human mobility analysis, and generative AI system design, ensuring both technical rigor and social relevance. This project aligns with the mission of the Center for Socially Responsible Artificial Intelligence (CSRAI) at Penn State by advancing human-centered, empirically grounded, and accountable AI systems that model how individuals interact with built environment during crises. It also lays the foundation for competitive external funding through programs such as NSF's Infrastructure Systems and People (ISP) and Cyber-Physical Systems and Connected Communities (CPS), positioning AURA as a scalable, socially responsible framework for AI-enabled urban resilience research.