



AI-Powered Tools for Safe Evacuation of Individuals During Emergencies

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University

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Research Needs

Emergency evacuation via transportation systems and infrastructure is a critical component of public safety, particularly in scenarios involving fires, transportation incidents, wildfires, and tsunamis. Even with progress in emergency management, significant challenges persist in ensuring the safe and efficient evacuation of individuals, particularly those who are vulnerable. The increasing complexity and frequency of these hazards necessitate innovative solutions to enhance preparedness and response mechanisms.

Fires in buildings and transportation hubs present immediate threats to human life and infrastructure (Gernay et al., 2016; Korolchenko & Pigurin, 2018; Li & Li, 2021). The National Fire Protection Association (NFPA, 2024) reports thousands of fire incidents annually, resulting in significant casualties and property damage. Traditional evacuation methods often fail to account for the needs of vulnerable users, who may require additional time and assistance to evacuate safely (Ahn et al., 2022; Sugiyama & Yamori, 2020; Yu et al., 2023). Wildfires, particularly in regions like the western United States, disrupt transportation networks, leading to hazardous air quality, road closures, and infrastructure damage. The U.S. Environmental Protection Agency (EPA, 2024) notes that the intensity and frequency of wildfires have

increased due to climate change. These events pose challenges for emergency responders and evacuees, exacerbated by the unpredictability of wildfire behavior. Coastal areas prone to tsunamis face unique evacuation challenges due to the short warning times and the need for rapid vertical and horizontal evacuation. The National Oceanic and Atmospheric Administration (NOAA, 2024) emphasizes the importance of timely and accurate dissemination of evacuation orders. However, existing systems often do not effectively reach all segments of the population, particularly those with disabilities or language barriers.

Research on emergency evacuation has traditionally focused on optimizing evacuation routes and improving communication strategies. Studies have demonstrated the potential of artificial intelligence (AI) and machine learning to enhance evacuation efficiency. For instance, the application of AI in dynamic route optimization can significantly reduce evacuation times (Jiang, 2019; Khalilpourazari & Pasandideh, 2021). Additionally, the use of IoT (internet of things) devices for real-time monitoring of environmental conditions can provide valuable data for decision-making during emergencies (Ahanger et al., 2024). However, there are still several knowledge gaps that need to be addressed:

- *Personalized Evacuation Plans*: Current emergency evacuation models often adopt a one-size-fits-all approach, which fails to account for the unique needs and capabilities of vulnerable individuals (Barnes et al., 2021; Manley et al., 2016; Meng et al., 2023). These vulnerable groups may include the elderly, people with disabilities, children, and those with limited language proficiency or access to technology. To ensure the safety and well-being of all evacuees, it is essential to develop AI-driven evacuation plans that are tailored to the specific needs of these vulnerable users.

Therefore, the **first research need** is to investigate and create personalized evacuation plans that consider various factors such as mobility limitations, communication needs, and access to resources. By incorporating these factors into AI-powered evacuation tools, emergency responders can better address the unique challenges faced by vulnerable populations during evacuations. This research should focus on understanding the specific requirements of different vulnerable groups, as well as developing algorithms and models that can effectively incorporate these factors into personalized evacuation plans.

- *Integration of Real-Time Data*: While there is a significant amount of research on using IoT devices for environmental monitoring (Al-Nabhan et al., 2019; Krytska et al., 2017; Wu, 2020), there is a notable gap in integrating this real-time data into evacuation decision-making processes. The potential for AI to synthesize data from multiple sources, such as weather patterns, traffic conditions, and infrastructure status, and provide actionable insights during emergencies is not yet fully realized.

The **second research need** is to explore methods for integrating real-time data from IoT devices into AI-powered evacuation tools. This integration would enable emergency responders to make more informed decisions based on up-to-date information, ultimately leading to more efficient and effective evacuations. Research in this area should focus on creating robust data integration frameworks, developing algorithms for real-time data analysis, and designing user-friendly interfaces that present actionable insights to emergency responders clearly and concisely. By

addressing these two research needs, we can significantly enhance the capabilities of AI-powered evacuation tools and improve emergency response outcomes.

The proposed research on AI-powered evacuation tools addresses critical national and regional needs by enhancing the safety and efficiency of emergency responses within transportation infrastructure systems. The research supports the U.S. Department of Transportation's (DOT) strategic goals of enhancing safety and resilience. The integration of AI and IoT in evacuation planning can significantly improve the efficiency of emergency responses, thereby reducing casualties and economic losses. Furthermore, the project contributes to the DOT's goal of leveraging advanced technologies to address complex transportation challenges. In regions prone to wildfires and tsunamis, such as the western United States and coastal areas, the research addresses specific vulnerabilities and enhances local emergency preparedness.

Research Objectives

This research project aims to develop personalized AI-driven evacuation plans tailored to the needs of vulnerable populations and that can adapt to real-time data from IoT devices.

Develop Personalized AI-Driven Evacuation Plans Adaptable to Real-Time Data

This objective focuses on creating AI-driven evacuation plans that are specifically tailored to the unique requirements of vulnerable groups, such as the elderly, people with disabilities, children, and/or those with limited language proficiency or access to technology. By incorporating factors such as mobility limitations, communication needs, and access to resources, we can develop personalized evacuation strategies that ensure the safety and well-being of all evacuees. Additionally, these plans will be designed to be adaptable to real-time data (such as from IoT devices), allowing for dynamic adjustments based on current conditions.

- ***Hypothesis:*** Personalized AI-driven evacuation plans that adapt to real-time data will significantly improve the safety and efficiency of evacuations for vulnerable populations compared to traditional one-size-fits-all approaches.
- ***Measurable Outcomes:***
 - Development and implementation of personalized evacuation algorithms that can integrate real-time data.
 - Evaluation of evacuation times and safety outcomes for vulnerable populations in simulated scenarios using real-time data inputs.
 - User satisfaction and feedback from vulnerable groups regarding the adaptability and effectiveness of the personalized evacuation plans.

By addressing this objective, the research will contribute to the development of innovative AI-powered solutions that enhance the safety and efficiency of emergency evacuations, with a particular focus on addressing the needs of vulnerable populations. The integration of real-time data ensures that the solutions developed are comprehensive, inclusive, and adaptable to various emergency scenarios.

Research Methods

Data

To achieve the research objective, we will assemble comprehensive datasets from multiple sources, focusing on evacuation scenarios involving fires, transportation incidents, wildfires, and tsunamis. The data will include:

1. Evacuation Plans and Algorithms

- **Historical Data:** Data on evacuation procedures and outcomes from emergency management agencies such as the Utah Department of Public Safety (DPS) and OpenFEMA.
- **Academic and Industry Reports:** Reports and academic papers detailing challenges faced by vulnerable populations during evacuations.
- **Crowd Behavior Data:** Data on crowd behavior in dense areas from previous evacuation drills and simulations, sourced from local emergency management exercises and research studies. For instance, at Utah State University (USU), we have access to data from a series of simulated evacuation events for populations with disabilities conducted at USU under National Institute on Disability, Independent Living, and Rehabilitation Research (NIDILRR) projects. These projects include "Experimental Research on Pedestrian and Evacuation Behaviors of Individuals with Disabilities: Theory Development Necessary to Characterize Individual-Based Models" (H133G110242) and "Bottom-Up Modeling of Mass Pedestrian Flows: Implications for the Effective Egress of Individuals with Disabilities." These data sets will provide a foundation for understanding the behaviors and challenges faced by individuals with disabilities in evacuation scenarios.

2. Real-Time Data from IoT Devices

- **Environmental Data:** Weather patterns, air quality indices, and wildfire spread data from sources such as the Environmental Protection Agency (EPA) and National Oceanic and Atmospheric Administration (NOAA).
- **Traffic Conditions:** Data on traffic volumes, congestion levels, and road closures from the Utah Department of Transportation (UDOT). This includes relative volumes or origins/destinations from vehicle probe data (Iteris ClearGuide) or Bluetooth sensors (Blynscy) for most Utah roadways.

3. Geospatial and Demographic Information

- **Geospatial data** on evacuation routes, population density, and urban infrastructure from the U.S. Census Bureau, Utah Automated Geographic Reference Center, and Utah Department of Transportation.
- **Socio-demographic data** to understand the specific needs of different vulnerable groups, including the elderly, disabled, and non-English speakers.

Analysis

We will employ a range of advanced analytical methods to synthesize and analyze the collected data, ensuring the development of effective AI-powered evacuation tools.

1. *Development of Personalized AI-Driven Evacuation Plans*

- Fine-Tuning Large Language Models (LLMs): Using techniques such as transfer learning to fine-tune pre-trained LLMs on evacuation-specific datasets. This process involves:
 - o Data Preparation: Curating and cleaning evacuation-related datasets.
 - o Training: Using frameworks like TensorFlow or PyTorch to fine-tune models such as Llama 3 or GPT-4.
 - o Validation: Evaluating model performance using metrics like accuracy, precision, and recall.
- Algorithm Design and Testing: Creating personalized evacuation plans using machine learning techniques such as decision trees and clustering algorithms.
- Simulation and Validation: Running simulations in controlled environments to test the effectiveness of these plans, using software such as AnyLogic or Pathfinder to model different evacuation scenarios and assess outcomes.

2. *Integration of Real-Time Data*

- Data Integration Framework: Develop a basic framework to integrate essential real-time IoT data.
- Predictive Modeling: Employing predictive models, such as time-series forecasting (ARIMA models) and deep learning techniques (e.g., LSTM networks), to anticipate and respond to changes in evacuation conditions.

3. *Evaluation of Decision-Making and User Interfaces*

- User Interface Design: Designing intuitive interfaces, incorporating human-centered design principles to ensure ease of use and quick access to critical information.
- Feedback Mechanisms: To continuously improve the system, and establish mechanisms for collecting and analyzing user feedback, particularly from vulnerable populations.

4. *Virtual Reality (VR) Simulations*

- Simulated Evacuation Scenarios: Creating realistic VR environments replicating scenarios like stadiums, urban centers, and transportation hubs. This allows for testing both common and extreme situations without real-world risks.
- User Interaction Analytics: Logging and analyzing user interactions within the VR environment to gain insights into behavior and areas for improvement.

Relevance to Strategic Goals

The proposed project aligns closely with several CTIPS and USDOT strategic goals. Primarily, it addresses the CTIPS statutory research priority area of preserving the existing transportation system by developing advanced AI-powered tools that enhance emergency evacuation procedures, thereby maintaining the safety and functionality of transportation infrastructure

during critical incidents. This contributes to the USDOT's primary strategic goal of Economic Strength and Global Competitiveness by ensuring that transportation systems remain reliable and efficient, even in emergencies, thus supporting economic stability and resilience. The project also aligns with the CTIPS secondary strategic goal of Equity and Transformation by focusing on the needs of vulnerable populations, ensuring that emergency responses are inclusive and equitable. Furthermore, the research supports USDOT's strategic goals of Safety, by improving evacuation efficiency and reducing risks during emergencies; Climate and Sustainability, by optimizing evacuation routes to minimize environmental impacts; and Transformation, by integrating cutting-edge AI and IoT technologies into emergency management practices. By advancing these strategic goals, the project will contribute to the overall excellence and modernization of the transportation system, ensuring it is robust, inclusive, and prepared for future challenges.

Educational Benefits

One Ph.D. student (Amir Rafe) will be involved in this project as a graduate research assistant. This student will gain valuable skills in project management, communication, and data management, alongside their existing discipline-specific expertise in emergency evacuation planning, AI and machine learning, and IoT data integration. The student will focus on assembling and managing various data sources, including real-time data and historical data on evacuation procedures. Additionally, they will conduct statistical and machine learning analyses to develop and validate AI-driven evacuation plans. The PhD student Rafe will take the lead on many of the research project's major tasks, including writing and presenting results. The findings and methodologies derived from the project will be incorporated into classroom instruction, providing real-world examples and case studies to enhance learning. This hands-on involvement will prepare the student for future careers in academia, industry, or public service, equipped with cutting-edge skills and experience in AI applications for emergency management. The PI Singleton teaches undergraduate/graduate-level courses on transportation data analysis, active transportation, and transportation planning.

Outputs through Technology Transfer

The findings of this research project will be disseminated to other researchers, professionals, and practitioners in several ways. We will share results with the research and professional community through presentations at local, national, and international conferences such as meetings of the Utah Department of Transportation, the Institute of Transportation Engineers, and the Transportation Research Board. In addition to the project report, we plan to prepare two manuscripts and submit them for publication in transportation and emergency management journals. The final report will be sent to transportation staff at state and local transportation and emergency management agencies and posted online. We will also provide a CTIPS webinar based on our project's results. Data management and analysis scripts will be shared with the research community on PI Singleton's (<https://github.com/singletonpa>) or PhD student Rafe's (<https://github.com/pozapas/>) GitHub pages. Furthermore, the fine-tuned LLM for crowd evacuation will be published on Hugging Face, making it accessible to other researchers and practitioners for further development and application.

Expected Outcomes and Impacts

This research is expected to yield significant advancements in the modeling, practices, and procedures for emergency evacuations, particularly for vulnerable populations. We anticipate creating a robust framework that improves evacuation efficiency and safety by developing personalized AI-driven evacuation plans and allowing for the integration of real-time data from IoT devices and other sources. These innovations will be beneficial for practitioners, providing actionable insights and optimized evacuation strategies tailored to diverse scenarios, including fires, transportation incidents, wildfires, and tsunamis. The project's outcomes will also have implications for future research, offering a foundation for further exploration into AI and IoT applications in emergency management. Tangible products resulting from this project will include prototype software for personalized evacuation planning, real-time data integration frameworks, user-friendly interfaces for emergency responders, and detailed guidebooks and instructional manuals for implementing these AI-powered tools in real-world scenarios. Additionally, the project will generate open-source data processing and analysis scripts, enhancing the research community's ability to build upon our findings and methodologies.

Work Plan

1. Review Literature on Emergency Evacuation and AI Applications

Review existing literature on emergency evacuation, focusing on AI-driven solutions, IoT data integration, and the needs of vulnerable populations. This includes a systematic search of research databases for journal articles, reports, and case studies. This task will be completed approximately 4 months after the project starts.

2. Assemble Data on Evacuation Scenarios, Real-Time IoT Data, and Demographics

Gather data on historical evacuation procedures, real-time IoT data (including traffic volumes, weather, and infrastructure status), and demographic information from sources such as the Utah Department of Transportation (UDOT), Utah Transit Authority, EPA, NOAA, and relevant GIS data. The task will be completed approximately 5 months after the project starts.

3. Perform Data Fusion on Assembled Datasets

Merge the collected data sources into a consistent dataset for analysis. This includes aligning data formats, handling missing data, and performing spatial interpolation to integrate air quality and weather data with traffic and evacuation data. The task will be completed approximately 7 months after the project begins.

4. Develop and Refine AI Models for Personalized Evacuation Plans Adaptable to Real-Time IoT Data

Fine-tune large language models (LLMs) on evacuation-specific datasets and develop personalized evacuation algorithms. This task includes designing the AI system to be adaptable based on real-time IoT data. Simulations will be conducted to test and refine the AI model in various evacuation scenarios. The initial focus will be on a small area and a short timeframe to refine the methods. This task will be completed approximately 11 months after the project starts.

5. Conduct VR Simulations for Validation

Create VR simulations to model different evacuation scenarios and validate the effectiveness of the AI-driven evacuation plans. Analyze user interactions to gain insights and improve the models. The task will be completed around 15 months after the project begins.

6. Prepare Reports, Presentations, and Publications

Compile the final report, prepare conference presentations, and write journal articles to disseminate findings. Additionally, develop instructional manuals and guidebooks based on the research outcomes. This task will be completed approximately 18 months after the project starts.

7. Technology Transfer and Dissemination

Execute the technology transfer plan by conducting webinars, workshops, and seminars. Share results on PI Singleton's research website and GitHub and publish the fine-tuned LLM on Hugging Face. This task will be completed approximately 18 months after the project starts.

Project Cost

Total Project Costs:	\$178,273.39
CTIPS Funds Requested:	\$ 89,136.39
Matching Funds:	\$ 89,137.00
Source of Matching Funds:	Utah LTAP

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