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Dynamic Evacuation Routing and Traffic Management Under Hurricane Threats: A Comprehensive Review

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Abstract: *Hurricanes represent a significant threat to human life and infrastructure, particularly in coastal regions where rapid and large-scale evacuations are necessary. Traditional evacuation strategies often suffer from limitations such as unpredictable hurricane behaviour, infrastructure constraints, and variable human response. This review explores dynamic evacuation routing and traffic management strategies aimed at addressing these challenges. It analyzes contraflow operations, evacuation implementations, and predictive traffic modeling, while also examining the transformative role of autonomous and connected vehicle technologies in enhancing evacuation efficiency. The integration of real-time data, advanced traffic simulations, and vehicular communication systems is emphasized as critical to improving evacuation outcomes. Despite progress, gaps remain in infrastructure readiness, public policy, and equitable access to smart mobility solutions. This paper highlights emerging trends and research needs, ultimately arguing for a multi-layered approach that combines technological innovation, policy development, and public engagement to enhance evacuation resilience under hurricane threats.*

Keywords: *Dynamic Routing, Hurricane Evacuation, Traffic Management, Autonomous Vehicles, Predictive Modeling*

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1.0 Introduction

Hurricanes pose significant threats to coastal regions worldwide, often resulting in loss of life, extensive property damage, and prolonged disruptions to socio-economic activities. As global climate change increases the frequency and intensity of hurricanes, coastal communities are more vulnerable than ever before. Evacuation remains the most critical life-saving strategy for populations at risk during such extreme weather events. However, the effectiveness of evacuations depends heavily on the accuracy of forecasts, the efficiency of route planning, the management of traffic flow, and public compliance with evacuation orders.

The dynamic nature of hurricanes—marked by their erratic paths, fluctuating intensities, and rapidly changing impact zones—presents a significant challenge to transportation authorities. Static evacuation plans, which are often based on historical storm data and fixed route assignments, fail to accommodate the real-time adjustments needed during an evolving disaster. As a result, traditional evacuation methods frequently lead to massive traffic congestion, significant delays, and heightened exposure to danger for evacuees. During events such as Hurricane Katrina (2005) and Hurricane Irma (2017), many evacuees were stranded on highways for hours due to poorly managed traffic flows and inadequate evacuation routing strategies.

In recent years, transportation engineering has seen a shift toward dynamic routing and real-time traffic management solutions. These advancements are facilitated by the increasing availability of big data, machine learning algorithms, sensor technologies, and intelligent transportation systems (ITS). For example, predictive traffic models using deep learning techniques such as Long Short-Term Memory (LSTM) networks have demonstrated the potential to forecast congestion and optimize routing under emergency conditions (Rahman & Hasan, 2022). Furthermore, technologies such as connected and autonomous vehicles (CAVs) are gaining attention for their potential role in enhancing the efficiency and safety of hurricane evacuations (Syed & Hasan, 2023).

A review of the existing literature reveals that while several models have been proposed for dynamic evacuation planning and traffic mitigation, they often lack scalability, integration of real-time meteorological data, or consideration of human behavioral factors. Many studies focus either on the technical feasibility of dynamic routing algorithms or on case-specific analyses without offering a holistic understanding of how various components—such as road infrastructure, vehicle autonomy, communication technologies, and human decision-making—interact during large-scale evacuations. Moreover, limited research has been conducted on how to practically deploy these technologies in heterogeneous traffic environments, particularly in low-resource or rural areas that often bear the brunt of hurricane impacts.

The aim of this study is to provide a comprehensive review of dynamic evacuation routing and traffic management strategies under hurricane threats. It explores how state-of-the-art technologies and methodologies can be leveraged to improve evacuation effectiveness and reduce vulnerability in at-risk populations. The review evaluates traditional and emerging evacuation models, the role of autonomous and connected vehicles, the integration of real-time data, and the implications for policy and infrastructure development.

The significance of this study lies in its potential to bridge the gap between theory and practice in disaster evacuation planning. By synthesizing current knowledge and identifying practical challenges and opportunities, this review serves as a valuable resource for transportation engineers, urban planners, emergency managers, and policymakers. It emphasizes the urgent need for dynamic, data-driven, and people-centered approaches to evacuation planning in the era of climate change and smart mobility. The insights from this study can inform the design of more resilient and adaptive evacuation systems that prioritize public safety and operational efficiency.

2.0 Challenges in Hurricane Evacuation Traffic Management

The management of traffic during hurricane-induced evacuations remains one of the most complex aspects of emergency response. While the goal of evacuation is to move at-risk populations to safety efficiently and quickly, numerous challenges—ranging from meteorological uncertainties to infrastructure constraints and human factors—can significantly hinder the process. Understanding these challenges is critical to developing dynamic, adaptive, and effective evacuation strategies.

2.1 Unpredictable Hurricane Behavior

The dynamic and often unpredictable behavior of hurricanes introduces significant uncertainty into the planning and execution of evacuation protocols. Hurricane trajectories and intensities can change rapidly due to varying atmospheric conditions, making it difficult for authorities to determine the optimal time and direction for evacuation. This unpredictability often results in two detrimental scenarios: premature evacuation, which may lead to unnecessary use of limited resources and heightened public anxiety, or delayed evacuation, which exposes residents to greater risk.

For instance, during Hurricane Irma in 2017, forecast models initially suggested a direct hit on Florida's east coast. However, the hurricane shifted westward, catching both residents and emergency planners off guard. As a result, there was widespread over-evacuation from areas that were not ultimately impacted, leading to severe congestion across evacuation corridors and a shortage of fuel and accommodations in unaffected areas (Zhang *et al*., 2021). The frequent updates in storm projections challenge the design of static evacuation plans, underscoring the need for real-time routing and dynamic traffic adjustment mechanisms.

2.2 Infrastructure Limitations

Another critical challenge is the limited capacity and fragility of transportation infrastructure, particularly in areas with high population densities or constrained geographic layouts. Many road networks in coastal regions are not designed to handle the sudden and massive surge in traffic that occurs during an emergency evacuation. Bottlenecks, limited lane availability, inadequate signage, and poorly maintained roads exacerbate the problem.

A notable example occurred during Hurricane Rita in 2005, when the evacuation of over 3 million people from the Houston and Galveston areas led to unprecedented gridlock. In many cases, travelers spent more than 20 hours attempting to reach safety, with some abandoning their vehicles due to fuel shortages and heat exhaustion. The situation revealed the vulnerabilities of urban transportation systems during peak evacuation loads and highlighted the absence of contingency plans such as contraflow lane reversals, traffic signal synchronization, and staging areas for fuel and emergency services.

In addition, rural areas often lack redundancy in road networks, making them highly susceptible to congestion or complete isolation if primary routes are compromised. The degradation of roads due to flooding or debris further limits evacuation effectiveness and complicates rescue and recovery operations.

2.3 Human Behavior and Compliance

Human factors play a pivotal role in the success or failure of evacuation efforts. While authorities can issue evacuation orders based on meteorological data and risk assessments, individual decision-making often diverges from official recommendations. Psychological variables such as perceived severity of the storm, prior experience with false alarms, trust in governmental institutions, and socioeconomic status influence evacuation behavior.

According to Rahman and Hasan (2022), a significant portion of the population may choose to delay departure until the last possible moment, either due to skepticism or a desire to protect property and pets. Others may lack access to transportation, face mobility limitations, or be unaware of the urgency due to communication barriers. These behaviors introduce irregularities in traffic flow, making it difficult to forecast and manage congestion patterns.

Non-compliance and delayed responses also increase the risk of vehicle clustering, particularly when large groups of evacuees depart simultaneously. This "evacuation wave" effect places enormous pressure on infrastructure and emergency response teams. Effective traffic management must therefore account for behavioral modeling and communication strategies that foster compliance, clarity, and timely action.

2.4 Coordination and Communication Gaps

Another layer of complexity is introduced by the fragmented coordination among federal, state, and local agencies responsible for managing evacuations. Discrepancies in risk perception, resource allocation, and policy priorities can lead to inconsistent messaging and operational delays. Communication

3.0 Dynamic Routing Strategies in Evacuation Scenarios

4.0 Integration of Autonomous and Connected Vehicle Technologies

Dynamic routing in evacuation scenarios refers to the real-time optimization and adjustment of traffic routes to accommodate changing road, weather, and demand conditions during a crisis such as a hurricane. Unlike static evacuation plans, which rely on pre-defined paths and schedules, dynamic routing employs real-time data feeds, sensor networks, and predictive algorithms to guide evacuees along the most efficient and safe paths. This approach significantly enhances traffic throughput, reduces congestion, and improves response time during emergencies. Several innovative strategies have been explored in the domain of hurricane evacuation, each with its unique strengths and operational considerations.

3.1 Contraflow Operations

Contraflow lane reversal is one of the most widely adopted strategies in mass evacuation scenarios. This technique involves reversing the direction of inbound traffic lanes to function as outbound routes, effectively doubling the available road capacity for evacuation traffic. The implementation of contraflow has been particularly prominent in states like Florida, Louisiana, and South Carolina, especially during large-scale evacuations ahead of major hurricanes.

However, contraflow operations are highly complex and demand meticulous planning and coordination among multiple agencies, including traffic police, transportation departments, and emergency management units. Key challenges include setting up physical barriers, reconfiguring traffic signals, and communicating the changes to the public in real time. Furthermore, access to fuel, rest stops, and emergency services along contraflow routes must be carefully managed to avoid secondary bottlenecks (Chiu *et al*., 2008).

3.2 Evaculane Implementation

The evaculane strategy designates the shoulder lanes of highways and major roads exclusively for evacuation use, providing additional capacity without requiring the full-scale inversion of traffic flow seen in contraflow operations. This approach was successfully piloted in Texas during Hurricane Ike, where shoulder lanes were opened to outbound vehicles to alleviate congestion on Interstate corridors (Songchitruksa *et al*., 2012).

Evaculane implementation has several advantages: it makes use of existing infrastructure, requires less logistical effort compared to contraflow, and can be rapidly deployed with temporary signage and enforcement. However, its effectiveness is limited to roads that have structurally sound and wide shoulders. Additionally, it may reduce accessibility for emergency vehicles if not carefully managed, raising safety concerns under certain conditions.

3.3 Predictive Traffic Modeling

With advances in artificial intelligence and data analytics, predictive traffic modeling has emerged as a transformative tool in evacuation planning. Models such as Long Short-Term Memory (LSTM) neural networks, agent-based simulations, and hybrid machine learning frameworks are increasingly used to simulate traffic scenarios, forecast congestion points, and suggest alternative evacuation routes in real time.

These models integrate multiple data streams, including historical traffic patterns, live GPS feeds, weather forecasts, social media activity, and meteorological projections, to generate dynamic route suggestions. For example, Jiang *et al*. (2024) developed a predictive LSTM model capable of forecasting traffic density across a city-wide network with high accuracy during Hurricane Dorian, demonstrating substantial improvements in route efficiency and travel time.

Nevertheless, the effectiveness of predictive modeling is highly dependent on data quality, availability, and computational infrastructure. In areas with poor data coverage or limited technological infrastructure, these models may yield suboptimal or outdated results.

Table 1: Comparison of Dynamic Routing Strategies

Strategy	Advantages	Challenges
Contraflow	Doubles evacuation capacity	Requires extensive coordination and planning
Evaculane	Utilizes existing road shoulders for evacuation	Limited to roads with suitable shoulder width
Predictive Modeling	Enables proactive and data-driven traffic management	Relies heavily on data accuracy and infrastructure

Table 1 presents a comparative overview of the three major dynamic routing strategies utilized in hurricane evacuation scenarios. Each strategy is evaluated in terms of its practical benefits and operational limitations.

Contraflow is shown to offer the highest increase in evacuation capacity by reassigning entire road directions, but this comes at the cost of extensive coordination, requiring human, technical, and financial resources.

Evaculane offers a simpler, more infrastructure-light solution, leveraging highway shoulders as temporary lanes. However, it is only viable on roads with shoulders wide and safe enough to support sustained vehicular flow.

Predictive Modeling provides a forward-looking approach to traffic management using artificial intelligence. While highly effective in theory, its real-world utility depends on access to high-quality, real-time data and robust computing platforms.

These strategies are not mutually exclusive and can be combined or adapted to suit the scale and geography of the evacuation area. Their strategic integration forms the backbone of next-generation dynamic evacuation systems.

4.0 Integration of Autonomous and Connected Vehicle Technologies

The integration of emerging vehicle technologies, specifically Autonomous Vehicles (AVs) and Connected Vehicles (CVs), offers transformative potential for improving the effectiveness and efficiency of hurricane evacuation strategies. These technologies support dynamic and adaptive traffic management by minimizing human error, optimizing route decisions, and enhancing real-time coordination across a transportation network under stress. As the frequency and intensity of hurricanes increase due to climate change, there is growing interest in deploying these technologies to address evacuation challenges such as congestion, delayed departures, and accessibility barriers.

4.1 Autonomous Vehicles in Evacuation

Autonomous Vehicles (AVs) operate using a combination of sensors, artificial intelligence, and machine learning algorithms to navigate without human intervention. In evacuation scenarios, AVs have the potential to standardize driving behaviour, eliminating erratic lane changes, inconsistent speeds, and driver hesitation that typically contribute to bottlenecks and accidents during mass movement events. Simulation studies by Syed and Hasan (2023) indicate that even a moderate penetration of AVs into the traffic stream can lead to marked improvements in overall traffic flow, particularly on arterial evacuation routes and highway corridors. The study found that AVs improved lane utilization, reduced start-stop waves, and decreased overall evacuation times by up to 30% in mixed traffic scenarios compared to traditional vehicle-only models. Furthermore, AVs can be programmed with prioritized evacuation protocols, ensuring that routes are selected based not only on traffic efficiency but also on proximity to the disaster impact zone and individual passenger needs.

4.2 Connected Vehicle Communication

Connected Vehicles (CVs) add an additional layer of intelligence to the evacuation process by enabling real-time communication between vehicles (Vehicle-to-Vehicle or V2V) and between vehicles and traffic infrastructure (Vehicle-to-Infrastructure or V2I). This networked approach allows for instantaneous information exchange regarding traffic conditions, road closures, weather hazards, and evacuation orders. The responsiveness of such systems dramatically improves route optimization and coordination, especially in rapidly evolving hurricane scenarios. According to Chang & Edara (2017), CV-enabled systems significantly enhance situational awareness and reduce travel delays by facilitating coordinated lane changes, ramp metering, and adaptive signal control. CV technology also plays a critical role in managing emergency vehicle access and creating dynamic detours to accommodate changes in storm paths or infrastructure damage.

Moreover, the synergy between CVs and central traffic management systems enables authorities to issue targeted instructions and alerts to specific groups of vehicles, such as those in high-risk flood zones or areas with limited egress options. This level of precision in evacuation planning was not previously achievable with conventional traffic control methods, underscoring the value of connected technologies in disaster preparedness and response.

4.3 Shared Autonomous Vehicles (SAVs)

Shared Autonomous Vehicles (SAVs), which combine the autonomy of AVs with the shared-use model of ride-hailing services, present a viable solution to one of the most pressing equity challenges in hurricane evacuation: the mobility of individuals who do not own or cannot operate a private vehicle. These groups often include the elderly, individuals with disabilities, low-income populations, and tourists unfamiliar with local geography. Traditional evacuation planning frequently overlooks the needs of such vulnerable populations, resulting in disproportionate risk and mortality during hurricanes.

Sevim *et al*. (2025) developed a simulation-based framework for deploying SAV fleets in rural and underserved urban areas, demonstrating that even a modest fleet size can substantially increase evacuation coverage and decrease total clearance time. Their study highlighted that SAVs, when coupled with real-time demand prediction algorithms, can dynamically respond to trip requests, re-route based on traffic congestion, and prioritize high-risk passengers. The inclusion of SAVs in evacuation strategy not only improves logistical efficiency but also promotes social equity by ensuring that no population segment is left behind due to a lack of personal transportation options.

In summary, the integration of AV, CV, and SAV technologies into hurricane evacuation plans marks a significant advancement in transportation engineering. These technologies allow for more precise, responsive, and inclusive evacuation processes, helping to mitigate the operational and humanitarian challenges associated with large-scale storm events. Their successful deployment, however, depends on overcoming technological, regulatory, and infrastructural hurdles, including data privacy concerns, vehicle interoperability, and the availability of supportive roadway systems. As these technologies mature, future evacuation strategies will increasingly rely on a hybrid ecosystem of smart vehicles and intelligent infrastructure to ensure safer, faster, and more equitable evacuations.

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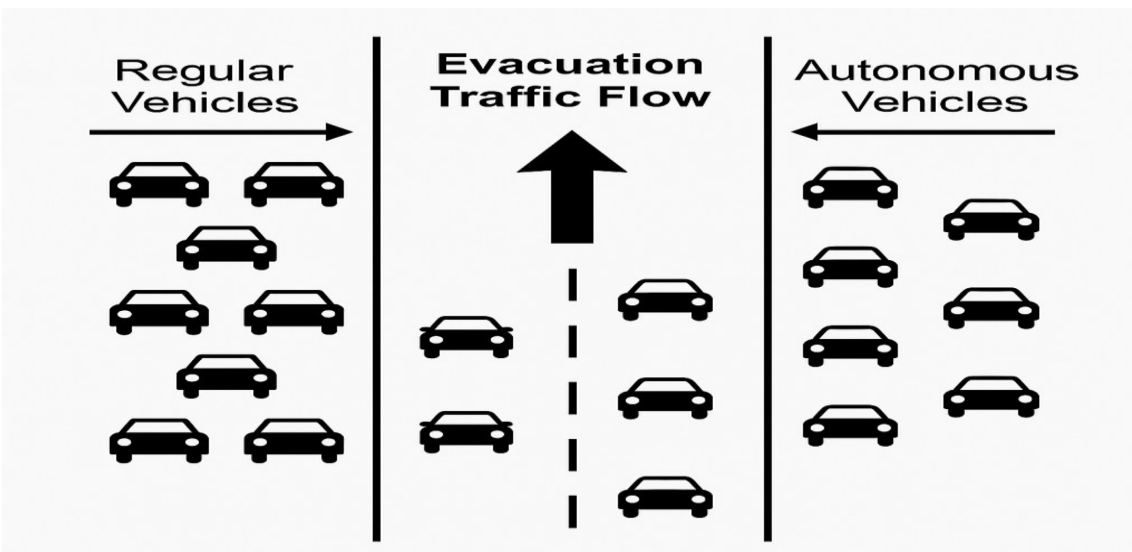

Fig. 1: Impact of AV Integration on Evacuation Traffic Flow

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5. 0 Future Directions and Conclusion

The integration of dynamic routing strategies and advanced vehicle technologies holds promise for improving hurricane evacuation outcomes. Future research should focus on: • Data Integration: Combining traffic, weather, and social media data to enhance predictive models. • Infrastructure Investment: Upgrading roadways to support dynamic routing and AV operations. • Policy Development: Establishing regulations and guidelines for the deployment of AVs and CVs in emergency scenarios. In conclusion, while challenges remain, the adoption of dynamic evacuation routing and advanced traffic management strategies can significantly enhance the effectiveness of hurricane evacuations, ultimately saving lives and resources.

5.0 Future Directions and Conclusion

The increasing frequency and severity of hurricanes, driven in part by climate change, demand innovative approaches to evacuation planning and execution. As demonstrated in this review, the fusion of dynamic routing strategies with emerging transportation technologies such as Autonomous Vehicles (AVs), Connected Vehicles (CVs), and Shared Autonomous Vehicles (SAVs) presents a promising frontier in hurricane evacuation management. However, fully realizing the potential of these solutions requires concerted efforts across several domains, particularly in data integration, infrastructure development, and policy formulation.

One of the most critical areas for future research and development is data integration. The effectiveness of dynamic routing during hurricane evacuation is heavily dependent on the accuracy and timeliness of data inputs. Current systems often rely on historical traffic patterns and pre-set evacuation plans, which may not reflect the rapidly evolving conditions during a hurricane event. Integrating real-time traffic data, meteorological forecasts, social media reports, and mobile phone location data can enhance the responsiveness of predictive traffic models. Such integration allows for a more nuanced understanding of evacuee behavior, congestion hotspots, and risk zones. For example, machine learning algorithms trained on multimodal datasets can generate more accurate route recommendations, helping reduce bottlenecks and ensure faster clearance times.

Simultaneously, infrastructure investment is essential to support the deployment of dynamic routing systems and AV/CV technologies. Many road networks in hurricane-prone regions were not designed with high-volume, bidirectional traffic flow in mind, and they lack the digital infrastructure required for vehicle-to-infrastructure (V2I) communication. Upgrades such as adaptive traffic signals, embedded sensors, digital signage, and dedicated evacuation lanes will be necessary to facilitate intelligent transportation systems (ITS). Additionally, the construction of resilient evacuation corridors that are less susceptible to flooding and debris blockages can further enhance the reliability of evacuation routes. Investment in rural infrastructure is also critical to ensure equitable access to safe evacuation for underserved communities.

From a governance standpoint, policy development must evolve in parallel with technological advancements. Current traffic regulations and emergency response plans rarely account for AV and CV operations, which may create legal ambiguities and coordination challenges during disaster scenarios. Future policies should address vehicle prioritization protocols, cybersecurity standards for connected systems, ethical frameworks for AV decision-making during emergencies, and liability issues in the case of technological failure. Establishing a clear regulatory environment will facilitate smoother integration of these technologies into existing emergency management systems.

In addition, inter-agency collaboration among emergency managers, transportation departments, meteorological agencies, and technology developers is crucial for creating cohesive evacuation plans that reflect both logistical and human factors. Public education campaigns will also be important to build trust in autonomous systems and ensure that communities understand how to interact with AVs and CVs during emergencies.

In conclusion, while significant challenges remain, the adoption of dynamic evacuation routing strategies and advanced traffic technologies has the potential to revolutionize hurricane evacuation management. By enabling real-time, data-driven decision-making, these innovations can reduce congestion, shorten evacuation times, and improve accessibility for vulnerable populations. Continued research, infrastructure modernization, and supportive policy frameworks will be essential to unlock these benefits. As hurricanes grow more unpredictable and devastating, leveraging intelligent transportation solutions offers a critical path toward saving lives and preserving societal resilience in the face of natural disasters.

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Declarations

Ethics and Consent to Participate
Not applicable.

Consent to Publish
Not applicable

Availability of data and materials
The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

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All components of the work were executed by the author