An Intelligent GIS And Meta-Heuristic Based Emergency Vehicle Routing Framework for Smart Urban Healthcare Systems

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Abstract- Emergency medical response systems play a critical role in reducing mortality during life-threatening situations where rapid transportation and timely intervention are essential. Existing ambulance routing and dispatch systems primarily rely on static distance-based navigation approaches that fail to account for dynamic urban challenges such as traffic congestion, infrastructure damage, signal interference, and unstable network connectivity. Several studies have explored GPS-enabled dispatching, GIS-based traffic systems, swarm intelligence algorithms, and Tele-EMS integration; however, most existing frameworks remain fragmented and lack real-time synchronization with smart-city infrastructure.This paper presents a comprehensive review of current emergency vehicle routing methodologies and identifies major research gaps in dynamic traffic integration, disaster-aware routing, network-aware navigation, and scalable urban routing architectures. Based on these gaps, a novel intelligent routing framework is proposed that combines GIS-based traffic synchronization, meta-heuristic optimization algorithms, predictive congestion analysis, and network-aware path planning. The proposed framework aims to improve ambulance response efficiency, reduce navigation delays, maintain stable Tele-EMS connectivity, and support adaptive routing during urban emergencies and disaster scenarios. The study contributes a structured review of existing approaches, identifies limitations in current systems, and proposes a scalable smart emergency transportation model for future urban healthcare infrastructure.

Keywords- Emergency Vehicle Routing GIS-Based Navigation Smart City Infrastructure Meta-Heuristic Optimization Tele-EMS Ambulance Dispatch Systems Swarm Intelligence

I. INTRODUCTION

1.1 Background of the Study

Emergency medical transportation systems are essential components of modern urban healthcare infrastructure. The effectiveness of ambulance routing directly affects patient survival, especially during the “Golden Hour” in trauma and cardiac emergencies. With increasing urban congestion and population density, traditional emergency dispatch systems face major operational challenges. Modern technologies such as GPS, GIS, IoT, and machine learning have improved emergency response capabilities, yet many routing systems still fail to adapt dynamically to real-time environmental conditions.

1.2 Problem Statement

Current emergency routing systems primarily depend on static shortest-path algorithms that do not adequately consider real-time traffic congestion, road blockages, disaster conditions, network stability, or urban signal interference. These limitations lead to delays in ambulance response time, inefficient routing, unstable Tele-EMS communication, and reduced patient survival rates.

1.3 Motivation

The increasing demand for efficient urban emergency response systems, combined with advancements in smart-city technologies, motivates the development of intelligent routing frameworks capable of real-time adaptation. Improving emergency vehicle navigation can significantly reduce mortality rates, improve

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DOI: https://doi.org/10.64388/IREV9I11-1717975

healthcare accessibility, and enhance disaster-response capabilities.

1.4 Objectives of the Study
- To evaluate the impact of mobile-integrated dispatch systems on navigation precision and response time.
- To develop and validate a meta-heuristic routing model for disrupted urban infrastructure.
- To analyze spatial-temporal congestion hotspots for predictive routing.
- To design a GIS-based synchronization framework for traffic signal pre-emption.
- To implement a network-aware routing system for stable Tele-EMS communication.
- To construct a scalable architectural framework capable of handling urban signal interference and data latency.

1.5 Contributions of the Paper
- Comprehensive review of emergency routing systems.
- Identification of major technical and infrastructural research gaps.
- Comparative analysis of traditional and intelligent routing algorithms.
- Proposed integrated GIS and meta-heuristic emergency routing framework.
- Development of a scalable smart-city compatible ambulance navigation model.

1.6 Organization of the Paper
Section 1 presents the introduction and research motivation. Section 2 reviews existing literature and identifies research gaps. Section 3 explains the proposed methodology and system architecture. Section 4 discusses expected outcomes and evaluation strategies. Section 5 highlights applications and use cases, while the final section concludes the paper and suggests future work.

II. RELATED WORK / LITERATURE REVIEW (CORE SECTION)

2.1 Thematic Classification of Literature

A. Mobile-Based Emergency Dispatch Systems
Existing studies explored mobile applications integrated with GPS and GPRS technologies for ambulance booking and emergency tracking. These systems improved communication efficiency but lacked dynamic traffic optimization and hospital coordination mechanisms.

B. Traditional and Meta-Heuristic Routing Algorithms
Researchers analyzed shortest-path algorithms such as Dijkstra, Bellman-Ford, and A* for emergency navigation. More recent studies introduced meta-heuristic approaches such as Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and Beetle Swarm Optimization (BSO) to improve adaptability in dynamic environments.

C. GIS and Smart-City Infrastructure Integration
Several smart-city frameworks proposed GIS-based traffic synchronization and adaptive traffic signal control for ambulance prioritization. However, implementation challenges remain due to uneven smart infrastructure deployment.

D. Network-Aware Tele-EMS Routing
Studies proposed routing approaches considering cellular connectivity for uninterrupted Tele-EMS communication. Most frameworks still struggle with dynamic network fluctuations and urban signal interference.

E. High-Dimensional and Dynamic Urban Routing
Advanced optimization techniques and kernel-based algorithms were introduced to improve scalability in large urban routing networks. However, real-time weight adaptation and contextual awareness remain limited.

2.2 Comparative Analysis of Existing Methods

Author/Paper	Method	Focus	Limitation
P01	Mobile GPS Dispatch	Ambulance booking and tracking	No real-time traffic adaptation
P02	A*, ACO Algorithms	Disaster rescue routing	Limited multi-objective optimization
P03	GIS Historical Analysis	Delay hotspot identification	Lack of predictive rerouting
P04	GIS Smart Corridors	Traffic signal synchronization	Hardware dependency
P05	Network-Aware A*	Tele-EMS communication	Static network assumptions
P06	Google Maps Architecture	Navigation infrastructure	Urban canyon interference
P07	Kernel-Based Optimization	Large-scale routing efficiency	Lack of dynamic weighting

Fig 4.2 Comparative Analysis of Existing Methods

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2.3 Critical Review

Existing emergency routing systems demonstrate significant improvements over traditional manual dispatch mechanisms; however, many systems remain limited by fragmented architecture and static routing assumptions. Traditional shortest-path algorithms fail in highly dynamic urban environments, while meta-heuristic approaches often require high computational resources. Smart-city frameworks depend heavily on advanced infrastructure availability, making them difficult to implement uniformly. Additionally, current systems inadequately address network reliability, disaster-aware adaptability, and large-scale real-time computation.

2.4 Identified Research Gaps

- Lack of integration between emergency routing and real-time traffic management.
- Limited disaster-aware adaptive routing mechanisms.
- Poor interoperability between ambulance systems and smart-city infrastructure.
- Weak handling of urban GPS interference and network instability.
- Limited scalability for large high-dimensional urban routing networks.
- Lack of predictive congestion-aware emergency navigation systems.

III. PROPOSED METHODOLOGY (DESIGN SECTION)

3.1 System Overview

The proposed framework integrates GIS-based navigation, swarm intelligence optimization, predictive congestion analysis, and network-aware routing to create an intelligent emergency response system. The architecture combines real-time traffic monitoring, smart traffic signal synchronization, cellular signal mapping, and adaptive route recalculation.

3.2 Workflow Diagram

Emergency Request → Mobile Dispatch System → GPS/GIS Data Collection → Traffic & Network Analysis → Meta-Heuristic Routing Engine → Traffic Signal Synchronization → Optimized Ambulance Navigation → Hospital Arrival

Fig 6.2 Workflow Diagram

3.3 Dataset Description

Datasets:

- GPS and GIS traffic datasets
- Historical ambulance movement datasets
- Urban traffic congestion data
- Cellular network signal strength datasets
- Smart-city sensor data
- Disaster road blockage datasets

Possible sources:

- Google Maps APIs
- OpenStreetMap
- USGS/NASA SRTM datasets
- Municipal traffic database

IV. EXPECTED RESULTS AND DISCUSSION

4.1 Expected Outcomes

- Reduced ambulance response time.
- Improved routing accuracy in urban environments.
- Better adaptability during disasters.
- Stable Tele-EMS connectivity.
- Improved scalability for smart-city emergency systems.

4.2 Comparative Evaluation Plan

Compare the proposed framework against:

- Dijkstra Algorithm
- A* Algorithm
- Ant Colony Optimization
- Particle Swarm Optimization

4.3 Discussion
The proposed system is expected to outperform traditional shortest-path methods by dynamically adapting to traffic, environmental conditions, and communication constraints by Integration with GIS (Geographic Information System).

V. APPLICATIONS AND USE CASES

- Industrial Use: The proposed emergency vehicle routing framework can be widely applied in healthcare transportation systems, smart-city infrastructure, and intelligent traffic management industries. Hospitals, ambulance service providers, and emergency response organizations can use the system to optimize ambulance dispatch operations and reduce emergency response times. Integration with smart traffic control systems can help municipal authorities improve urban mobility and emergency corridor management. Additionally, logistics and transportation industries may adapt the proposed routing and optimization techniques for dynamic fleet management and real-time route planning.
- Social Impact: The system has significant social benefits by improving the speed and reliability of emergency medical services during critical situations. Faster ambulance response can reduce mortality rates and improve patient survival during accidents, cardiac emergencies, and disaster situations. The framework also enhances accessibility to healthcare services in densely populated urban environments by minimizing delays caused by traffic congestion and infrastructure limitations. During natural disasters or public emergencies, the system can support efficient rescue coordination and emergency healthcare delivery, ultimately contributing to public safety and community well-being.
- Policy Relevance: The proposed framework supports government initiatives related to smart-city development, intelligent transportation systems, and digital healthcare transformation. Policymakers and urban planning authorities can use the framework to design traffic prioritization strategies for emergency vehicles and improve emergency response infrastructure. The system can also contribute to national disaster management policies by enabling adaptive emergency routing during crises. Furthermore, the integration of GIS, traffic analytics, and communication systems aligns with modern urban mobility and public health policies focused on sustainable and technology-driven city management.
- Academic Value: From an academic perspective, the study contributes to research in intelligent transportation systems, emergency healthcare logistics, GIS-based routing, and meta-heuristic optimization. The framework provides a foundation for future research on adaptive emergency navigation, predictive traffic analysis, and network-aware routing algorithms. Researchers can further extend the proposed model using machine learning, IoT devices, and real-time smart-city data. The study also offers valuable insights for interdisciplinary research combining computer science, transportation engineering, healthcare informatics, and urban planning.

CONCLUSION

This paper presented a comprehensive review of existing emergency vehicle routing and ambulance dispatch systems, focusing on the challenges associated with urban congestion, dynamic traffic conditions, disaster scenarios, and communication instability. The literature analysis revealed that many traditional routing approaches rely heavily on static shortest-path algorithms that are insufficient for modern smart-city emergency response requirements. Several important research gaps were identified, including limited integration with real-time traffic systems, lack of adaptive disaster-aware routing, poor handling of urban network interference, and inadequate scalability in large metropolitan environments. To address these limitations, this study proposed an intelligent GIS-based and meta-heuristic emergency routing framework that combines real-time traffic analysis, predictive congestion management, smart traffic signal synchronization, and network-aware navigation.

The proposed framework aims to improve ambulance response efficiency, reduce transportation delays, maintain stable Tele-EMS communication, and enhance overall emergency healthcare logistics. By integrating swarm intelligence optimization techniques with smart city infrastructure, the system offers a scalable and adaptive solution for future emergency transportation systems.

The research contributes both a structured review of current methodologies and a novel conceptual framework that can support the development of intelligent urban healthcare systems. Future work may involve implementation of the proposed model using real-world traffic datasets, IoT-enabled infrastructure, and machine learning-based predictive analytics for enhanced emergency response optimization.

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