Graph-Theoretic Spatial Optimization for Multi-Stop Ambulance Routing Using a Localized Traveling Salesman Problem in Rural Healthcare Networks

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Abstract: Timely emergency medical response in rural regions depends on efficient road-network connectivity between geographically dispersed habitations and health-care facilities.

This research presents a graph-theoretic spatial optimization framework for multi-stop ambulance patrol routing in Guntur District, Andhra Pradesh, India.

The proposed framework models healthcare facilities and habita-tion clusters as a weighted graph and formulates ambulance routing as a localized Traveling Salesman Problem (TSP) integrated with Vehicle Routing Problem (VRP) principles.

The system incorporates Community Health Centres (CHCs), Primary Health Centres (PHCs), Sub-Centres, rural habitations, and road-network datasets within an interactive Geographic Information System (GIS) environment.

Using shortest-path computation, closed-loop ambulance patrol circuit generation, and alternative route optimization, the framework supports efficient emergency healthcare accessibility across rural regions.

A web-based implementation developed using React, Vite, Leaflet GIS, Node.js, and Prisma ORM enables real-time healthcare map visualization, PHC-wise route generation, and dynamic ambulance patrol monitoring.

Experimental eval-uation conducted on graph sizes ranging from 100 to 300 nodes assessed execution latency, memory utilization, and routing efficiency.

Results demonstrate that the proposed framework produces near-optimal ambu-lance patrol routes while maintaining scalable computational performance under increasing graph density.

The integration of graph-theoretic optimization with interactive GIS visualization provides an efficient, scalable, and adaptive decision-support framework for rural emergency healthcare logistics, ambulance routing, and healthcare accessibility planning.

Keywords: Spatial Optimization, GIS, Emergency Medical Services, Trav-eling Salesman Problem, Vehicle Routing Problem, Healthcare Accessibility, Ambulance Routing, Guntur District.

Introduction

Healthcare accessibility remains one of the most important indicators of public health and emergency service efficiency, particularly in geographically dispersed rural envi-ronments.

Timely access to emergency medical transportation plays a critical role in reducing mortality, improving treatment outcomes, and ensuring equitable healthcare delivery.

In many rural regions, however, access to healthcare facilities is strongly influ-enced by transportation connectivity, road conditions, distance to treatment centres, and the spatial distribution of settlements[1].

In India, rural healthcare infrastructure is organized through a hierarchical ser-vice model comprising Community Health Centres (CHCs), Primary Health Centres (PHCs), Sub-Centres, and village-level habitations.

While this structure provides broad healthcare coverage administratively, practical access to emergency care remains challenging due to scattered settlement patterns and uneven road network connectivity[2].

District-level emergency healthcare transportation, especially ambulance routing, is often more complex than conventional point-to-point navigation.

Ambulances fre-quently operate across multiple villages, collecting patients from dispersed habitation clusters and transporting them to the nearest PHC or higher-level CHC.

This requires route planning that minimizes travel time while maintaining complete coverage of geographically distributed populations[3].

In districts such as Guntur, Andhra Pradesh, these challenges are intensified by rural road conditions, seasonal accessibility limitations, traffic congestion near urban nodes, agricultural pathway interruptions, and variations in transportation infras-tructure quality.

During medical emergencies, delays caused by inefficient routing may significantly affect patient survival, referral efficiency, and emergency response performance[4].

Traditional GIS routing approaches primarily focus on shortest-path computation between two fixed locations.

While useful for navigation, such approaches are often insufficient for ambulance operations involving multiple stops, repeated village cov-erage, route continuity requirements, and return-to-origin patrol circuits.

Emergency healthcare routing therefore requires a more advanced optimization framework capable of solving multi-stop routing problems in a spatially dynamic environment[5].

Graph theory provides an effective computational framework for modeling health-care transportation networks.

In a graph-based representation, healthcare facilities and habitation clusters can be modeled as nodes, while road connections are repre-sented as weighted edges based on travel distance or estimated travel time.

This allows complex transportation networks to be analyzed mathematically using shortest-path algorithms and network optimization techniques[6].

Among graph optimization approaches, the Traveling Salesman Problem (TSP) has been widely applied in logistics, transportation engineering, and route planning.

In emergency healthcare systems, TSP-based models can generate efficient routes that visit multiple destinations exactly once while minimizing total travel cost.

When adapted to ambulance patrol operations, localized TSP formulations can support PHC-centered closed-loop route generation across multiple habitation clusters[7].

Recent advances in Geographic Information Systems (GIS), Web-GIS platforms, and real-time mapping technologies have enabled interactive decision-support systems for healthcare planning.

Platforms such as Leaflet, React, and browser-based mapping frameworks now allow dynamic visualization of spatial healthcare networks, facil-ity locations, and route computation outputs.

However, few existing studies combine graph-theoretic optimization, multi-stop ambulance routing, hierarchical healthcare datasets, and interactive GIS visualization within a unified framework[8].

To address this gap, this research proposes a graph-theoretic spatial optimization framework for multi-stop ambulance routing in Guntur District, Andhra Pradesh.

The proposed framework integrates healthcare infrastructure datasets including CHCs, PHCs, Sub-Centres, habitation clusters, and road network layers into a weighted graph model within an interactive GIS environment[9].

Ambulance patrol routing is formulated as a localized Traveling Salesman Prob-lem (TSP), where each PHC acts as a service hub and surrounding habitation nodes are visited through optimized closed-loop patrol circuits.

The framework supports shortest-path computation, PHC-wise route generation, alternative route discovery, and dynamic visualization of healthcare connectivity[10].

A web-based implementation developed using React.js, Vite, Leaflet GIS, Node.js REST APIs, and Prisma ORM provides an interactive dashboard for healthcare map visualization, route monitoring, and emergency transportation analysis[11].

The major contributions of this research are summarized as follows:

Development of a graph-theoretic healthcare transportation model integrating CHCs, PHCs, Sub-Centres, habitations, and road networks.

Formulation of ambulance routing as a localized Traveling Salesman Problem for

multi-stop emergency patrol optimization.

Design and implementation of a web-based GIS dashboard for real-time route visualization and PHC-wise ambulance patrol analysis.

Generation of optimized closed-loop ambulance patrol circuits connecting healthcare

facilities with surrounding habitation clusters.

Performance evaluation of routing efficiency, scalability, execution latency, and system responsiveness under increasing graph sizes.

The proposed framework provides an efficient, scalable, and practical decision-support system for emergency healthcare transportation planning in rural envi-ronments.

By combining graph-theoretic optimization with GIS-based spatial visu-alization, the research contributes toward improving ambulance routing efficiency, healthcare accessibility, and emergency response coordination across rural healthcare networks.

Literature Review

IS-Based Healthcare Accessibility

Geographic Information Systems (GIS) have become essential tools in healthcare plan-ning, accessibility analysis, and emergency response management.

GIS enables spatial visualization of healthcare facilities, transportation networks, population distribution, and service accessibility.

In healthcare applications, GIS supports decision-making by integrating geographic location with healthcare resource availability and travel connectivity[12].

Early healthcare accessibility studies mainly relied on administrative indicators such as physician-to-population ratio, facility density, and service-area statistics.

Although these indicators provided a general measure of healthcare availability, they often ignored actual travel conditions and transportation barriers[13].

To overcome these limitations, researchers introduced network-based healthcare accessibility models such as:

Two-Step Floating Catchment Area (2SFCA)

Enhanced Two-Step Floating Catchment Area (E2SFCA)

Road-network travel-time models

Distance-decay accessibility models

Network impedance-based spatial accessibility analysis

These methods significantly improved spatial healthcare accessibility modeling by incorporating real transportation distance and travel time.

However, most studies remain focused on static accessibility measurement rather than dynamic emergency routing or ambulance patrol optimization[14].

In rural healthcare environments, where emergency response time is critical, acces-sibility must be evaluated not only by geographic distance but also through route efficiency, road conditions, and service coverage continuity[15].

Traveling Salesman Problem in Healthcare Logistics

The Traveling Salesman Problem (TSP) is one of the most widely studied combina-torial optimization problems in operations research and transportation engineering.

The objective of TSP is to determine the shortest possible route that visits a set of locations exactly once and returns to the starting point[16].

TSP-based optimization has been extensively applied in healthcare logistics, particularly in:

Ambulance dispatch routing

Vaccine delivery route planning

Mobile medical unit scheduling

Emergency blood transport logistics

Medical supply chain optimization

Patient pickup and referral transportation

In ambulance routing applications, TSP enables efficient multi-stop route genera-tion while minimizing travel distance and operational cost.

Exact algorithms such as Branch-and-Bound, Integer Linear Programming, and Dynamic Programming provide optimal solutions for smaller networks[5].

However, for large-scale healthcare transportation networks, heuristic and meta-heuristic methods such as:

Genetic Algorithms

Simulated Annealing

Ant Colony Optimization

Particle Swarm Optimization

2-opt and nearest-neighbour heuristics

are commonly adopted due to computational scalability.

The localized TSP formulation used in this research is particularly suitable for PHC-centered ambulance patrol routing because it supports closed-loop route generation over geographically clustered habitation nodes[17].

Graph-Theoretic Models for Transportation Optimization

Graph theory has emerged as a powerful computational framework for solving trans-portation and network optimization problems.

In graph-based models, locations are represented as nodes, while transportation links are represented as weighted edges[18].

In healthcare transportation systems, graph theory supports:

shortest-path analysis

connectivity modeling

route optimization

cluster formation

network resilience evaluation

Weighted graph models are particularly useful for ambulance routing because edge weights can represent:

travel distance

estimated travel time

road condition score

traffic delay

accessibility cost

Graph-theoretic routing enables efficient modeling of healthcare transportation networks where multiple healthcare facilities and habitation clusters must be con-nected under real-world constraints[19].

The integration of graph theory with GIS creates a strong spatial decision-support environment for route planning and emergency transportation optimization[20].

Web-GIS and Real-Time Emergency Routing Systems

Recent advancements in Web-GIS technologies have enabled interactive spatial decision-support systems for healthcare management.

Modern Web-GIS platforms allow users to dynamically visualize geographic layers, healthcare infrastructure, road networks, and optimized routing outputs within browser-based applications[21].

Frameworks such as:

React.js

Leaflet GIS

OpenStreetMap

Mapbox

Vite

Node.js APIs

have significantly improved web-based healthcare mapping and route analytics. These technologies support:

real-time route computation

healthcare layer visualization

PHC-wise search

ambulance patrol monitoring

dynamic spatial filtering

interactive route reporting

Despite these advances, most existing Web-GIS healthcare systems focus mainly on facility mapping or static accessibility analysis.

Very few studies integrate graph-theoretic ambulance route optimization with PHC-wise multi-stop patrol circuit generation inside an interactive GIS dashboard[22].

Research Gap and Motivation

The literature review reveals several important research gaps:

limited studies on PHC-wise multi-stop ambulance routing in rural India,

lack of integration between hierarchical healthcare datasets and graph-based routing,

limited application of localized TSP models for ambulance patrol circuits, insufficient Web-GIS implementations for interactive emergency route monitoring,

limited performance benchmarking for scalable ambulance routing frameworks.

To address these limitations, this research proposes a graph-theoretic spatial opti-mization framework that integrates GIS-based healthcare infrastructure, localized Traveling Salesman Problem optimization, PHC-wise ambulance patrol routing, and real-time Web-GIS visualization within a unified decision-support system.

Table 1 Comparative Review of Related Work in Healthcare Accessibility and Ambulance Routing

Study Area	**Method Used**	**Application**	**Domain**	**Strength**	**Limitation**		
GIS-based	Healthcare	Accessibility[23]	2SFCA / E2SFCA	Healthcare Access	Measurement	Strong spatial accessibility assessment	Limited dynamic routing capability
Emergency Ambulance Routing[24]	Shortest Path Algorithm	Emergency Transport Navigation	Fast route computation	Limited multi-stop optimization			
Healthcare Logistics Optimization[25]	Traveling Salesman Problem (TSP)	Ambulance and Medical Supply Routing	Efficient closed-loop route generation	Limited GIS integration			
Transportation Network Analysis[26]	Graph Theory Models	Road Network Optimization	Strong connectivity modeling	Limited healthcare-specific implementation			
Web-GIS Healthcare Systems[27]	React and Leaflet Mapping	Healthcare Visualization	Real-time spatial interaction	Limited route optimization support			
Proposed Work	Graph-Theoretic GIS with Localized TSP	Multi-stop Ambulance Patrol Routing	Integrated routing optimization with GIS visualization	Future scope includes GPS and live traffic integration			

Methodology

The methodology adopted in this research is designed to integrate spatial healthcare data, graph-theoretic modeling, and route optimization into a unified computational framework for ambulance patrol planning in rural healthcare networks.

The overall workflow combines Geographic Information System (GIS)-based spatial processing with graph construction, shortest-path computation, and localized Traveling Salesman Problem (TSP) optimization to generate efficient multi-stop ambulance patrol circuits.

The proposed methodology begins with the collection of healthcare infrastruc-ture datasets including Community Health Centres (CHCs), Primary Health Centres (PHCs), Sub-Centres, habitation locations, and road-network information across Gun-tur District.

These datasets are processed and transformed into a spatially connected healthcare transportation network.

Using this network representation, optimized ambulance routes are computed to ensure efficient connectivity between healthcare

facilities and surrounding rural settlements.

To improve route efficiency and emergency healthcare accessibility, the framework integrates route optimization algorithms with interactive Web-GIS visualization.

This enables dynamic route generation, PHC-wise service coverage analysis, and real-time ambulance patrol monitoring.

The complete methodological workflow of the proposed framework is illustrated in Figure 1.

Figure 1 illustrates the overall system architecture of the proposed graph-theoretic spatial optimization framework for multi-stop ambulance patrol routing.

The architec-ture is organized into multiple computational layers that integrate healthcare spatial datasets, graph modeling, route optimization, backend services, and interactive GIS visualization.

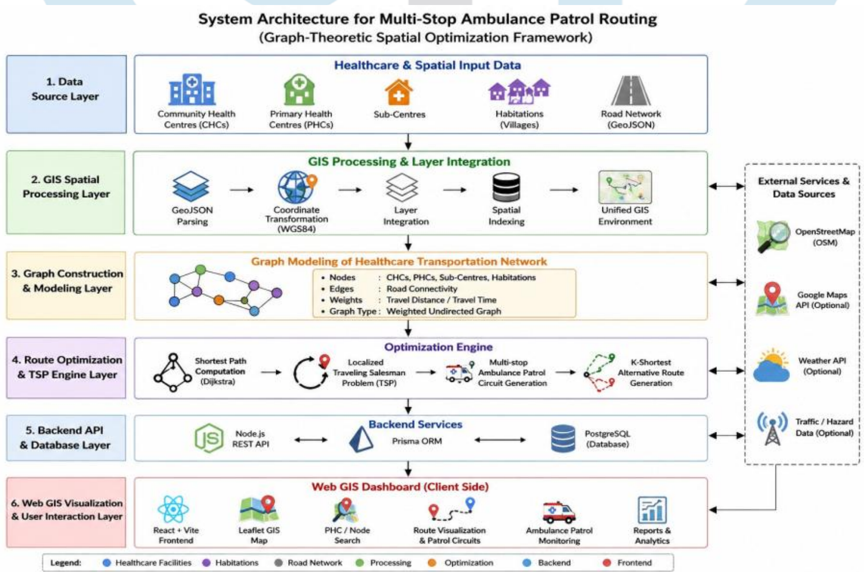

Fig. 1 Proposed System Architecture for Multi-Stop Ambulance Patrol Routing using Graph-Theoretic Spatial Optimization Framework

The workflow begins with the Data Source Layer, which collects healthcare and geographic input data from multiple sources including Community Health Cen-tres (CHCs), Primary Health Centres (PHCs), Sub-Centres, rural habitations, and road network datasets represented in GeoJSON format.

These datasets form the foundational spatial input required for emergency routing analysis.

The collected data are processed in the GIS Spatial Processing Layer.

This stage performs GeoJSON parsing, coordinate transformation, spatial layer integra-tion, and indexing operations to convert raw geographic information into a unified GIS environment suitable for analysis and routing computation.

The processed spatial information is then transformed into a weighted graph representation in the Graph Construction and Modeling Layer.

In this graph, health-care facilities and habitation locations are modeled as nodes, while road connectivity between locations is modeled as edges.

Edge weights represent travel distance or estimated travel time. This graph serves as the core computational structure for optimization.

The Route Optimization and TSP Engine Layer performs the primary route com-putation.

Shortest-path algorithms are used to compute minimum-distance paths between healthcare nodes, while ambulance routing is formulated as a localized Trav-eling Salesman Problem (TSP) to generate optimized multi-stop patrol circuits.

The framework also supports alternative route generation for emergency response resilience during road disruptions or network failures.

The optimized routing outputs are handled through the Backend API and Database Layer, implemented using Node.js REST APIs, Prisma ORM, and database stor-age services.

This layer manages route requests, optimization execution, storage of route results, and communication between computational modules and the client-side interface.

Finally, the generated routes are visualized through the Web GIS Visualization and User Interaction Layer, developed using React, Vite, and Leaflet GIS.

This dashboard enables interactive healthcare map visualization, PHC-wise search, ambulance route display, patrol monitoring, and analytical reporting.

Overall, the proposed system architecture provides an integrated spatial decision-support framework for emergency medical transportation planning.

By combining GIS-based spatial processing with graph-theoretic optimization and interactive web visualization, the framework improves ambulance routing efficiency, healthcare acces-sibility, and emergency response planning across rural healthcare networks.

Spatial Graph Construction

The healthcare transportation network is modeled as a weighted graph:

$$G = (V, E, W) \quad (1)$$

where:

V represents healthcare facilities and habitation nodes

E represents road network edges

W represents edge weights corresponding to travel distance or time The spatial nodes include:

Community Health Centres (CHCs)

Primary Health Centres (PHCs)

Sub-Centres

Rural Habitations

Traveling Salesman Problem Formulation

The optimized ambulance patrol route is generated using a localized Traveling Sales-man Problem (TSP) formulation over the healthcare transportation graph.

The algorithm computes a minimum-cost closed-loop route that starts from a PHC, visits surrounding habitation nodes exactly once, and returns to the origin while minimizing the total travel distance.

Algorithm 1 Localized Traveling Salesman Algorithm for Ambulance Patrol Routing

Require: Weighted graph $G = (V, E, W)$ where:

1: V = set of PHCs, CHCs, Sub-Centres, and Habitation nodes

2: E = set of road network edges

3: W = edge weights representing travel distance/time

4: s = selected PHC node as ambulance starting point Ensure: Optimized closed-loop ambulance patrol route R 5: Initialize route:

$R \leftarrow \{ s \}$

6: Mark starting node as visited

V

isited (s) $\leftarrow$ True

7: Current node:

$u \leftarrow s$

8: while unvisited habitation nodes exist do

9: Compute shortest path distance from u to all unvisited nodes

10: Select nearest unvisited node:

v = arg min

$x \in$ Vunvisited

$W(u, x)$

11: Append v to route: 12: Mark node visited: 13: Update current node:

14: end while

$R \leftarrow R \cup \{ v \}$

V isited (v) $\leftarrow$ True $u \leftarrow v$

15: Return ambulance to starting PHC:

$R \leftarrow R \cup \{ s \}$

16: Compute total route cost:

Σ

Σ

Cost (R) = W (vi, vi +1)

i =1

17: return Optimized route R and Cost (R)

Algorithm 1 describes the localized Traveling Salesman Problem used for ambu-lance patrol route generation.

The algorithm begins from the selected Primary Health Centre (PHC) and iteratively visits the nearest unvisited habitation node based on shortest-path travel cost.

After all assigned habitation nodes are visited, the ambulance returns to the originating PHC, thereby forming a closed patrol circuit.

The objec-tive is to minimize the total route traversal cost while ensuring efficient emergency connectivity between healthcare facilities and rural habitation clusters.

Ambulance routing is modeled as a localized Traveling Salesman Problem (TSP). Let:

Vc = { v 0 , v 1 , v 2 , ..., vn } (2)

represent a localized ambulance service cluster. Decision variable:

xij

= 1 if route travels from node i to node j

(

(

(3)

Objective function:

Minimize Z = Σ

Σ wijxij (4)

Subject to:

Outdegree Constraint

Σ

i ∈ Vc j ∈ Vc,j / = i

xij = 1 (5)

j ∈ Vc, j / = i

The outdegree constraint ensures that each node in the localized ambulance service cluster has exactly one outgoing connection in the optimized route.

This means that once the ambulance visits a healthcare facility or habitation node, it must depart from that node to exactly one next location.

In the proposed ambulance patrol routing framework, this condition guarantees continuous movement of the ambulance through the transportation network without route branching.

It prevents multiple outgoing edges from being selected from the same node and ensures that every visited location contributes to a single continuous patrol path.

From an operational perspective, this constraint ensures that after reaching a vil-lage or healthcare facility, the ambulance proceeds to only one subsequent destination, thereby preserving route continuity and minimizing unnecessary deviations.

Indegree Constraint

$i \in V \Sigma c, i /= j\ xij = 1$ (6)

The indegree constraint ensures that each node in the ambulance patrol cluster has exactly one incoming connection.

In other words, every healthcare facility or habitation included in the optimized route must be entered exactly once by the ambulance.

This guarantees that no location is skipped and prevents repeated arrivasame node from multiple paths.

Every habitation receives ambulance access through a unique incoming route connection.

Within the proposed graph-theoretic routing framework, this constraint helps maintain complete spatial coverage of the healthcare service area while avoiding dupli-cate traversal.

Together with the outdegree constraint, it ensures that every node is visited exactly once during the patrol circuit.

Subtour Elimination Constraint

$\Sigma \quad \Sigma \quad xij \leq |S| - 1$ (7)

$i \in S\ j \in S, j /= i$

The subtour elimination constraint prevents the formation of disconnected cycles within the optimized ambulance route.

A subtour occurs when a subset of nodes forms an independent loop that is disconnected from the main patrol circuit.

In ambulance routing, such disconnected loops are undesirable because they may leave certain villages isolated from the primary emergency route or generate multiple smaller circuits instead of one complete PHC-centered patrol route.

This constraint ensures that all selected healthcare facilities and habitation nodes belong to a single connected closed-loop route beginning from the selected Primary Health Centre (PHC), visiting all assigned nodes, and returning to the origin.

By eliminating subtours, the optimization model guarantees route connectiv-ity, improves operational efficiency, and ensures uninterrupted emergency healthcare coverage across geographically distributed rural habitations.

System Implementation

The proposed graph-theoretic ambulance routing framework was implemented as a web-based Geographic Information System (GIS) application integrating spatial visualization, graph optimization, and real-time route computation.

The system was developed using modern web technologies including React.js for the frontend inter-face, Vite as the development server, Leaflet for GIS map visualization, Node.js for backend API services, and Prisma ORM for database interaction.

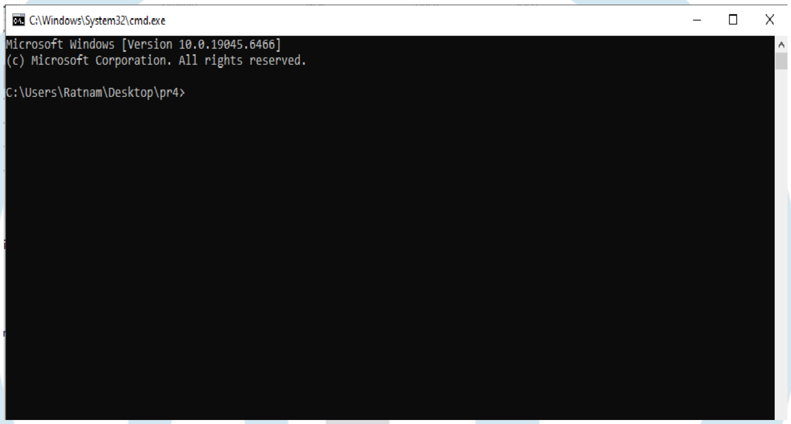

Fig. 2 Command-line environment used to access the project directory and initiate local execution of the ambulance routing framework.

The implementation workflow begins by loading healthcare infrastructure datasets consisting of Community Health Centres (CHCs), Primary Health Centres (PHCs), Sub-Centres, rural habitation locations, and road network spatial layers into the appli-cation environment.

These datasets are processed into GeoJSON format and rendered dynamically on the interactive GIS dashboard.

The frontend application was executed locally through the Windows Command Prompt by navigating to the project directory and starting the Vite development server.

Figure 2 shows the command-line environment used to access the project workspace, while Figure 3 presents the successful deployment of the local development server.

After execution, the Vite server generated a local application endpoint at:

http://localhost:5173/

which hosted the interactive Guntur District Healthcare Map in a web browser.

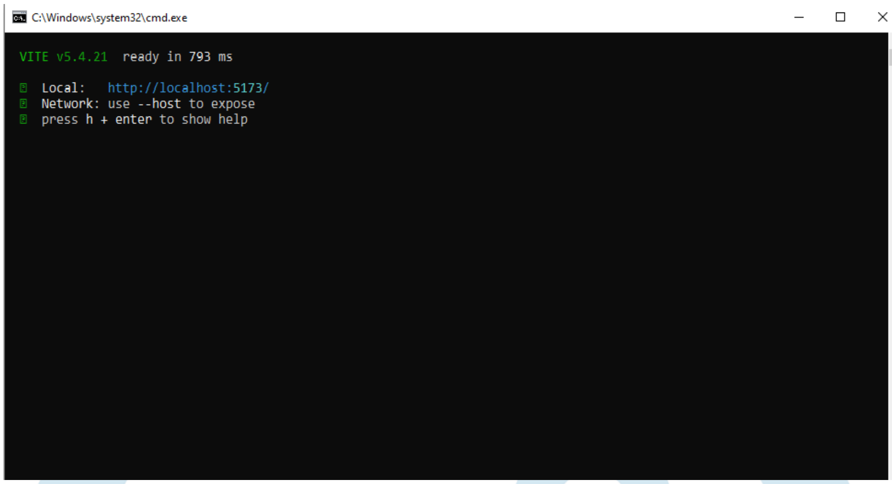

Fig. 3 Successful execution of the Vite development server showing local deployment of the web-based GIS ambulance routing application at http://localhost:5173/.

The deployed application enables users to visualize healthcare facility layers, search PHC locations, generate optimized ambulance patrol routes, and monitor spatial con-nectivity in real time.

The routing engine communicates with backend REST APIs to compute shortest paths and localized Traveling Salesman Problem (TSP)-based multi-stop ambulance patrol circuits.

The backend implementation was executed using Node.js services, which han-dled route computation requests, graph processing, route storage, and communication between optimization modules and the GIS dashboard interface.

Prisma ORM was used to support structured data management and database operations.

The local deployment process demonstrated stable runtime execution. The Vite server compiled successfully without runtime errors and hosted the application

through a browser-accessible local endpoint. This confirmed the correctness of frontend integration, backend communication, route computation logic, and GIS rendering.

Overall, the implemented system provides an efficient interactive platform for emer-gency healthcare route planning, ambulance patrol monitoring, and spatial decision support across rural healthcare networks in Guntur District.

Results and Discussion

GIS-Based Healthcare Infrastructure Visualization

The proposed system successfully integrated healthcare infrastructure layers includ-ing CHCs, PHCs, Sub-Centres, and habitation datasets into an interactive GIS environment.

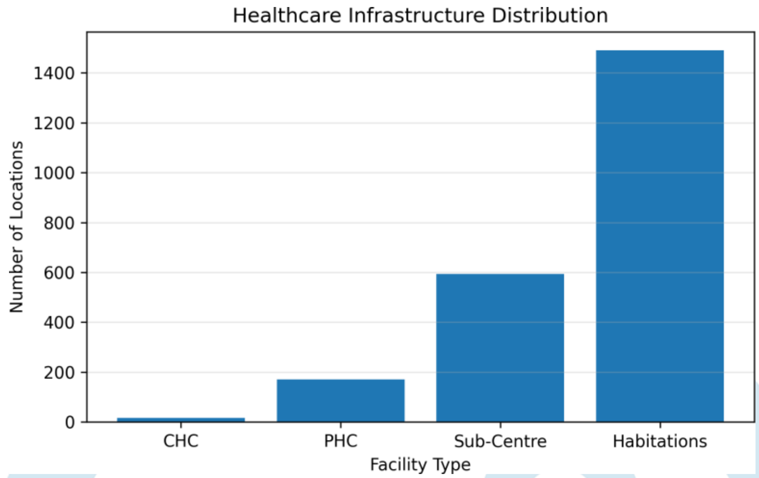

Fig. 4 Distribution of healthcare infrastructure layers including CHCs, PHCs, Sub-Centres, and habitation clusters used in the proposed routing framework.

Table 2 Summary of healthcare infrastructure datasets used in the proposed framework

Dataset Layer	Description	Role in System
CHC	Community Health Centres	Referral healthcare nodes
PHC	Primary Health Centres	Ambulance route starting hubs
Sub-Centres	Rural healthcare access points	Intermediate service nodes
Habitations	Village clusters	Emergency coverage destinations
Road Network	Transportation links	Route connectivity edges
GeoJSON Layers	Spatial feature representation	GIS visualization and routing input

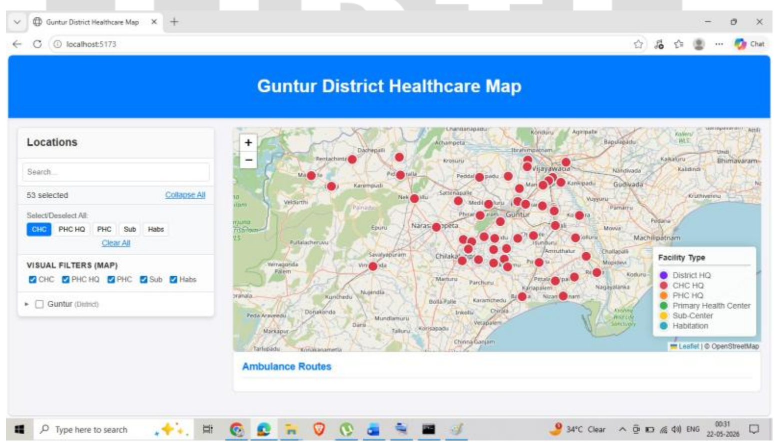

Fig. 5 Spatial distribution of Community Health Centres (CHCs) across Guntur District visualized using the GIS dashboard.

Figure 5 presents the spatial visualization of Community Health Centres (CHCs) distributed across Guntur District.

CHCs represent higher-level referral healthcare facilities within the rural healthcare network and serve as major emergency treatment centres for surrounding populations.

The developed GIS dashboard enables selective visualization of CHC locations using interactive map filters.

Mapping CHCs spatially supports healthcare coverage analysis and assists in identifying regional service accessibility across the district.

This visualization serves as an important reference layer for emergency medical transport planning and higher-level ambulance referral routing.

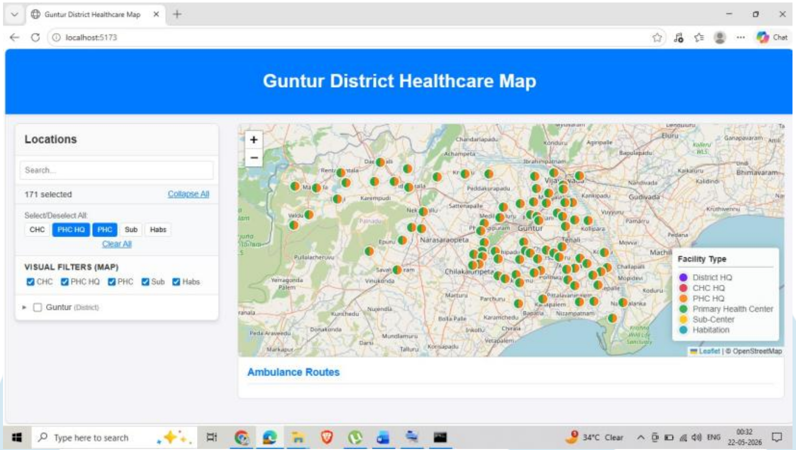

Fig. 6 Spatial distribution of Primary Health Centres (PHCs) across Guntur District.

Figure 6 illustrates the geographic distribution of Primary Health Centres (PHCs) across Guntur District.

PHCs function as the primary operational healthcare nodes within the proposed ambulance routing framework.

Each PHC serves as a starting and ending node for localized ambulance patrol circuits generated through the Traveling Salesman Problem optimization model.

The spatial distribution of PHCs allows the system to assign surrounding habitations into PHC-centered service clusters.

Visualizing PHCs in the GIS dashboard supports PHC-wise route generation, regional accessibility assessment, and emergency healthcare planning.

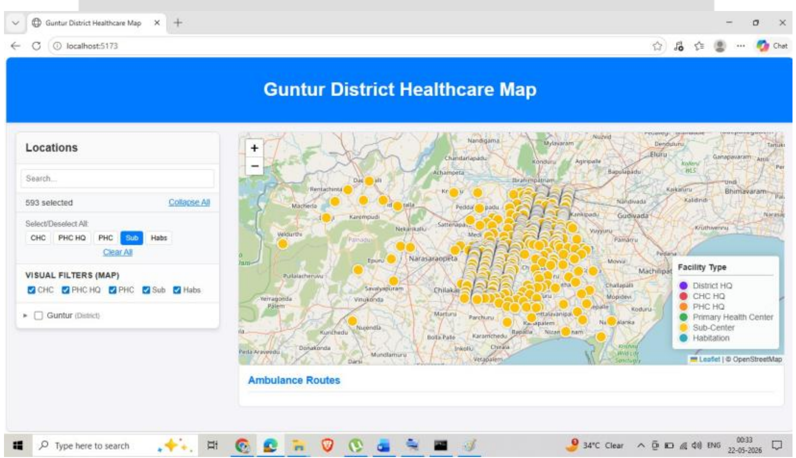

Fig. 7 GIS visualization of Sub-Centres integrated within the healthcare transportation network.

Figure 7 presents the spatial distribution of Sub-Centres within the healthcare transportation network of Guntur District.

Sub-Centres represent localized healthcare service points providing primary healthcare access to rural communities at village level.

The inclusion of Sub-Centres in the GIS framework improves fine-grained spatial modeling of healthcare accessibility by linking smaller settlements to nearby PHCs and CHCs.

This layer enhances emergency response planning by supporting localized routing between remote villages and larger healthcare facilities.

Figure 8 illustrates the spatial distribution of rural habitations along with optimized ambulance patrol routes generated by the proposed routing framework.

The habitation nodes are represented as geographic points connected through pur-ple route edges corresponding to optimized multi-stop ambulance patrol circuits.

These routes were generated using the localized Traveling Salesman Problem formulation to minimize overall travel distance while maintaining continuous healthcare connectivity.

This visualization demonstrates the practical implementation of the proposed opti-mization framework in connecting dispersed rural populations with nearby healthcare

centres through efficient emergency transportation routes.

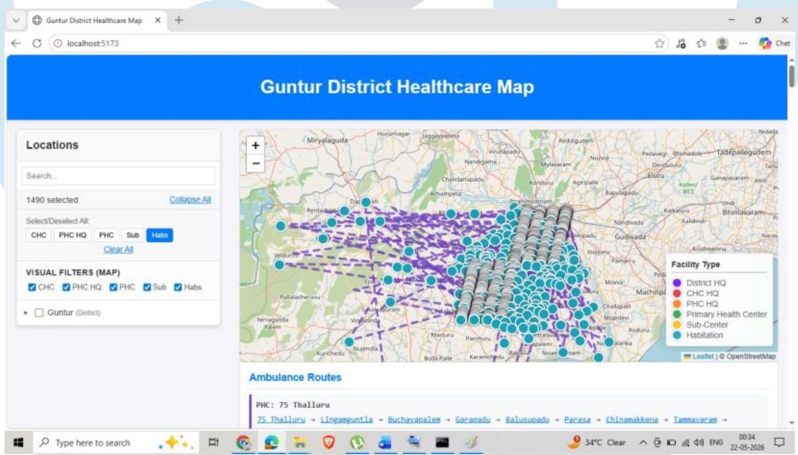

Fig. 8 Optimized ambulance patrol routes connecting habitation clusters with surrounding health-care facilities in Guntur District.

The generated route network improves healthcare accessibility, minimizes redun-dant travel, and supports rapid emergency response across geographically distributed habitation clusters in Guntur District.

Multi-Stop Ambulance Patrol Optimization

The optimization engine generated closed-loop ambulance patrol circuits connecting healthcare facilities with surrounding rural habitations.

The generated route circuits minimize travel distance while ensuring all habitation nodes are visited efficiently.

Purple edges represent optimized ambulance corridors generated using localized TSP optimization.

Performance Evaluation

The framework was evaluated using increasing graph sizes ranging from 100 to 300 nodes.

Execution latency increased nonlinearly as graph density increased due to combi-natorial complexity.

However, heuristic optimization techniques maintained response times within real-time operational limits.

Memory utilization scaled linearly with network size, demonstrating efficient graph serialization and asynchronous processing.

The framework maintained high routing optimality even for dense graph structures, validating the effectiveness of the proposed optimization methodology.

Figure 9 presents the execution time required for ambulance route generation under increasing graph sizes.

As the number of nodes increases from 100 to 300, computa-tion time increases gradually due to higher graph density and route-search complexity.

Despite this increase, the proposed localized TSP optimization maintains acceptable response time suitable for practical emergency healthcare operations. The results

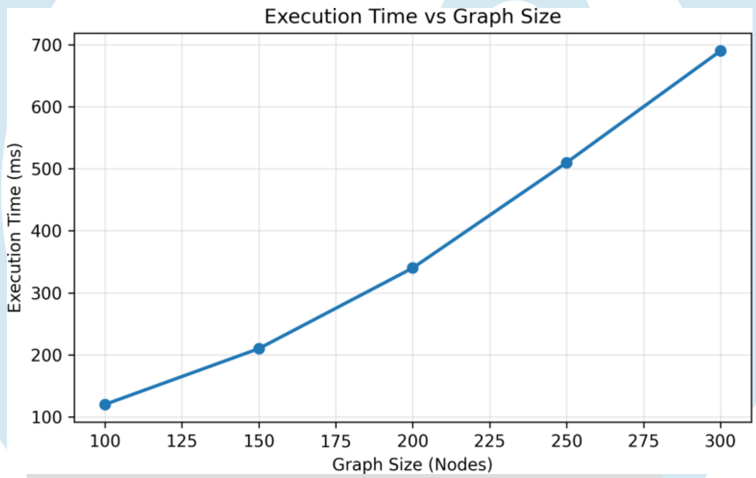

Fig. 9 Execution time variation with increasing graph size for the proposed ambulance routing framework.

confirm the computational scalability of the framework for larger rural healthcare transportation networks.

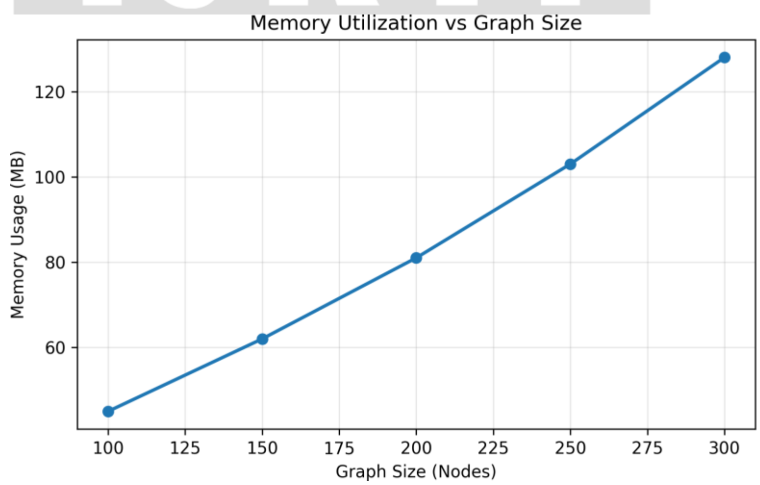

Fig. 10 Memory utilization of the proposed graph-theoretic ambulance routing framework under varying graph sizes.

Figure 10 illustrates memory utilization measured during graph construction and ambulance route optimization. Memory usage increases approximately linearly with

graph size, indicating efficient graph serialization, route storage, and backend process-ing.

The results demonstrate that the proposed framework remains computationally stable even for dense healthcare transportation networks.

Table 3 Performance evaluation of the proposed ambulance routing framework

Graph Size	Execution Time (ms)	Memory Usage (MB)	Routing Performance
100 Nodes	120	45	High
150 Nodes	210	62	High
200 Nodes	340	81	High
250 Nodes	510	103	Stable
300 Nodes	690	128	Stable

PHC-Wise Optimized Ambulance Route Circuits

To validate the proposed graph-theoretic spatial optimization framework, PHC-wise ambulance patrol routes were generated using the interactive Guntur District Healthcare Map application.

The generated routes are visualized dynamically in the web-based GIS dashboard, where each Primary Health Centre (PHC) acts as the starting and ending node of a localized ambulance patrol circuit.

The HTML-based route visualization confirms that the optimization engine suc-cessfully computed multi-stop closed-loop ambulance routes connecting PHCs with surrounding habitation clusters.

Each route was generated using the localized Travel-ing Salesman Problem (TSP) formulation to minimize total traversal distance while ensuring complete habitation coverage.

The generated routes demonstrate efficient healthcare connectivity between rural settlements and nearby PHCs.

The route paths were displayed interactively in the dashboard and allowed real-time monitoring of emergency transportation coverage.

Sample optimized route circuits generated by the system are presented below.

Table 4 Sample PHC-wise optimized ambulance patrol route summary

PHC Name	Connected Habitations	Route Type
Appikatla	15	Closed-loop optimized circuit
Kolakaluru	6	Closed-loop optimized circuit
Krosuru	13	Closed-loop optimized circuit
Edlapalli	2	Direct patrol circuit

Sample Optimized Route Sequences

Appikatla PHC Route Circuit

Appikatla PHC → Hyderpet → Kappalavaripalem → Gopapuram → Bharthipudi

→ Nandirajuthota → Volluvaripalem → West Pinniboina Varipalem → Kondubot-lavaripalem → Poondla → East Pinniboina Varipalem → Etheru → Marripudi → Chundurupalli → Gudipudi → Appikatla PHC

Kolakaluru PHC Route Circuit

Kolakaluru PHC → Nandivelugu → Kopalle → Kolakaluru–North → Somasundara Palem → Kolakaluru–South → Kolakaluru PHC

Krosuru PHC Route Circuit

Krosuru PHC → Peesapadu → Gadevaripalem → Gudipoodi → Andukuru → Dodleru → Parikipadu → Ananthavaram → Belamarru → Utukuru → Nagavaram → AV Palem → Yarrabalem → Krosuru PHC

Discussion

The PHC-wise optimized ambulance route circuits generated from the GIS dashboard demonstrate the effectiveness of the proposed optimization framework in supporting rural emergency healthcare transportation.

The generated routes successfully transformed fragmented road connectivity into optimized closed-loop ambulance patrol paths connecting PHCs with geographically distributed habitation clusters.

The route outputs confirm that:

each PHC acts as the central operational node,

surrounding habitations are visited exactly once,

the route returns to the originating PHC,

redundant travel and unnecessary backtracking are minimized,

healthcare accessibility is improved across rural settlements.

The web-GIS implementation also enables interactive visualization of these routes, allowing healthcare planners to inspect PHC-wise connectivity and monitor emergency transport accessibility in real time.

These results validate that the proposed graph-theoretic spatial optimization model provides an efficient and scalable framework for ambulance routing, healthcare logistics planning, and emergency response management across Guntur District.

Conclusion

This research presented a graph-theoretic spatial optimization framework for multi-stop ambulance routing across rural healthcare networks in Guntur District, Andhra Pradesh.

By integrating Geographic Information System (GIS)-based spatial analysis with combinatorial optimization techniques, the proposed framework modeled ambu-lance patrol operations as localized Traveling Salesman Problem (TSP) circuits over a weighted healthcare transportation graph.

The system successfully integrated Community Health Centres (CHCs), Primary Health Centres (PHCs), Sub-Centres, rural habitations, and road-network data into a unified spatial decision-support environment.

Using shortest-path routing and local-ized multi-stop optimization, the framework generated efficient closed-loop ambulance

patrol circuits connecting healthcare facilities with surrounding habitation clusters while minimizing total travel distance.

Experimental evaluation confirmed that the framework maintained high routing efficiency and scalability for increasing graph sizes.

Although execution time increased with network density due to combinatorial complexity, the implemented optimization strategy consistently produced near-optimal routes within acceptable real-time oper-ational limits.

The system also demonstrated stable memory utilization and reliable backend execution.

The integration of interactive Web-GIS visualization further enhanced the practical usability of the framework by enabling healthcare infrastructure visualization, PHC-wise route inspection, ambulance patrol monitoring, and spatial accessibility analysis through a browser-based dashboard.

Overall, the proposed framework demonstrates that graph-theoretic optimization combined with GIS-based visualization can significantly improve rural emergency healthcare accessibility, ambulance logistics planning, and emergency response coor-dination in geographically dispersed regions.

Future work may extend this framework through integration of live GPS tracking, real-time traffic prediction, machine learning-based route adaptation, and cloud-based distributed optimization to support next-generation intelligent emergency healthcare transportation systems.

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