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Optimization of Public Transport Route Accessibility in High Congestion Areas Using Arc GIS: A Case Study of Rawalpindi City

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Abstract
Due to increasing urbanization and environmental concerns, there is a growing need to enhance and optimize public transportation systems to make them more accessible, efficient, and sustainable. The aim of this study is to improve the public transportation network by optimization of the routes in high congested areas of Rawalpindi city. Geographic Information Systems (GIS) have emerged as a powerful tool for achieving such goal. The integration process involves collecting and analyzing geospatial data, including route information, passenger demographics, and real-time traffic conditions, to optimize transit routes. By incorporating real-time traffic data into the GIS model, the analysis provided insights into congestion configurations and prospective solutions. GIS-based maps presented performance metrics such as reduced travel times, enhanced accessibility scores, and better public transport usage. These metrics were critical for validating the proposed solutions and ensuring their feasibility for implementation. GIS-based route optimization study also proposed BRT systems in our study area (Rawalpindi) to create efficient, timesaving, and passenger-centric public transport options. To maximize its impact, cities need to encourage people to switch from cars to BRT. The success of a GIS-based optimization transportation system requires close collaboration between the public and private sectors.
Keywords
Geographic Information Systems (GIS), multimodal transportation, route optimization, Dijkstra's algorithm, accessibility analysis, traffic congestion management

1 Introduction

Public transport networks across the world are vital to urban mobility, acting as critical frameworks for improving accessibility, decreasing traffic congestion, and promoting environmental sustainability. Global urbanization has increased the demand for effective public transport networks significantly. According to United Nations figures, more than 55% of the world's population lives in cities, with that percentage expected to rise to 68% by 2050 (United Nations, 2018). This rapid urbanization has put tremendous pressure on existing transportation infrastructure, resulting in issues such as longer travel times, greater vehicle emissions, and a decline in urban quality of life (Madhu et al., 2024). Traffic congestion affects urban transport equity, with unequal access, higher accident risks and greater exposure to pollution and noise, disproportionately impacting pedestrians and cyclists (Gössling, 2016; Martens, 2012). A recent study revealed that high number of private vehicles on Pakistani roads cause congestion issues. The most evident result of this congestion is the growth in travel time, mainly during peak hours. These factors not only disturb the flow of traffic but also affect economy and human health ultimately (Farooq et al., 2024).

According to a World Health Organization (WHO) report, Pakistan ranks first in Asia and 48th worldwide in terms of traffic deaths (WHO, 2015). In addition, a health survey found that road accident mortality was greater than any other form of injury in Pakistan (WHO, 2009). Furthermore, Pakistan has the highest proportion of compact automobiles in the world, which contributes to traffic congestion (Syed et al., 2014). Traffic safety difficulties in

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Pakistan may be attributed to increased traffic, a lack of planning, reckless driving behaviour, no traffic separation, speeding, ignorance of traffic regulations, poor vehicle condition, terrible road conditions, and a large number of motorcycles on the road (Ahmed et al., 2019; Noman et al., 2020).

Developed cities such as London, New York, and Singapore have successfully used modern technology, notably Geographic Information systems (GIS), to optimize and integrate their multimodal transportation networks (Madhu et al., 2024). These cities have improved connection across multiple forms of transport by using GIS, as well as introducing real-time information systems to assist effective route planning, hence boosting overall passenger satisfaction and urban sustainability (de Palma and Picard, 2005).

GIS technologies are increasing in popularity for transportation planning because they allow for the visualization, analysis, and optimization of geographical data, allowing policymakers to build integrated public transportation networks (Bekhor et al., 2006). In London, for example, GIS has been critical to the development of the Oyster Card system, which analyses passenger movement patterns to optimize routes and timetables, providing fair accessibility (Rodrigue et al., 2020). Similarly, Singapore's transport network, which includes buses, trains, and even pedestrian walkways, use GIS to offer real-time traffic updates, reducing interruptions and delays (Fang et al., 2011). These worldwide results demonstrate GIS' revolutionary potential in tackling urban transportation difficulties, particularly in densely populated places where multimodal integration is critical to reduce reliance on private automobiles (Singh and Behera, 2019). Beyond improving mobility, such systems help to reduce greenhouse gas emissions, which aligns with global sustainability goals (Waddell, 2002).

In contrast, developing nations confront particular problems in constructing effective public transit networks. The simultaneous challenges of growing urbanization and limited infrastructure impede these cities' ability to build flawless, multimodal networks (Abubakar et al., 2017). Uncoordinated transport networks in South Asian cities cause congestion, increased emissions, and unequal access to options for mobility (Papinski and Scott, 2011). In Pakistan, for example, the urban population is predicted to rise dramatically, from 75 million in 2020 to more than 100 million by 2050. Population expansion and growing urban boundaries have pushed up transportation demand in cities like as Karachi, Lahore, Islamabad, and Rawalpindi. However, the lack of connectivity among public transportation modes, along with a large growth in private car ownership (estimated at 15% per year), exacerbates traffic congestion and environmental deterioration. The World Bank estimates that traffic congestion in Pakistan's largest cities costs $1 billion per year, which includes wasted fuel, lost productivity, and environmental damage (Zhu and Levinson, 2015).

In Pakistan's major centres, the twin towns of Rawalpindi and Islamabad demonstrate the need of modernizing public transport networks. Rawalpindi, with a 2.2% yearly population growth rate, is facing increasing hurdles in satisfying its citizens' mobility demands. The city's present public transportation network is divided, consisting of buses, vans, and informal transportation services that are not integrated with one another. This disconnected system not only frustrates commuters, but also leads to an overreliance on private automobiles, which contributes to severe traffic congestion and poor air quality. The lack of multimodal connection wastes resources and restricts access for underserved citizens, such as low-income groups and peri-urban inhabitants (Chadha and Garg, 2019).

The integration of Geographic Information Systems (GIS) offers a transformational solution to these difficulties, providing a data-driven approach to enhancing public transit accessibility and efficiency (Papinski and Scott 2011). GIS facilitates the gathering, processing, and visualization of geographical data, allowing urban planners to create optimal transportation networks that solve important mobility concerns. GIS-based multimodal integration in Rawalpindi has the ability to connect disparate modes of transport, cut commuting times, and improve equitable mobility access (Singh et al., 2015). By analysing geographical data on population density, transportation movement, and existing infrastructure, GIS can detect accessibility gaps and recommend targeted actions. For example, optimizing bus routes based on demand and geography can improve service coverage while lowering operating costs. Furthermore, real-time traffic monitoring using GIS can assist alleviate congestion by dynamically modifying transit routes and plans (Singh and Behera, 2019).

The use of GIS-based transport systems in Rawalpindi is consistent with worldwide best practices, as demonstrated by successful implementations in places such as Singapore and New York (Huynh, 2022; Pelletier et al., 2011). These cities illustrate GIS's efficiency in integrating various means of transport and enhancing passenger experiences via real-time updates and smooth route changes. Singapore's transit system, for example, uses GIS and IoT-enabled technologies to dynamically change bus timetables in response to passenger demand, optimizing resource allocation and lowering wait times (Panahi and Delavar, 2008). In a similar way New York City has used GIS to identify underprivileged neighbourhoods, prioritize infrastructure improvements, and implement accessibility measures like lifts and ramps at subway stations. These examples demonstrate how GIS may close service gaps, reduce dependency on private cars, and reduce greenhouse gas emissions, all of which are critical for improving urban sustainability (Tasgaonkar et al., 2024).

Rawalpindi has the potential to benefit greatly from GIS-based multimodal integration. A coherent public transportation network would solve numerous important concerns at once, including traffic congestion, environmental degradation, and social disparities. The existing dependence on private automobiles increases carbon emissions, exacerbating urban air quality issues. Implementing an optimized public transportation system using GIS would stimulate a modal shift, pulling commuters away from private automobiles and towards shared mobility choices. This shift might dramatically reduce traffic congestion on important roadways like Murree Road and Kacheri Chowk, which have been identified as critical bottlenecks by local research. Furthermore, using GIS to expedite route design and increase intermodal connection will help not only everyday commuters, but also marginalized groups who today face obstacles to viable transportation alternatives.

The larger advantages of GIS go beyond operational savings. GIS systems may promote equitable transportation planning by merging demographic data and real-time analytics, ensuring that all population segments, including women, children, and the elderly, have access to safe and efficient public transportation (Ralston, 2000). Furthermore, the environmental impact of GIS-based transportation systems is significant. By optimizing routes and timetables, such systems cut fuel consumption and emissions, in line with Pakistan's international commitments, such as the Paris Agreement. The creation of an integrated transport network also promotes the United Nations Sustainable Development Goals (SDGs), notably SDG 11, which aims to make cities more inclusive, safe, resilient, and sustainable (Chadha and Garg, 2019).

While the potential benefits are obvious, adopting GIS-based multimodal integration in Rawalpindi presents various hurdles. Data availability and quality are important to the effectiveness of these systems. GIS models rely on accurate, real-time traffic and demographic data to perform properly. In Pakistan, the lack of comprehensive geospatial information and the fragmentation of public transit records offer considerable challenges. To create effective data-sharing frameworks, government agencies, corporate organizations, and academic institutions must cooperate together. Furthermore, public awareness and adaptation are critical factors in the success of GIS-based systems. Initiatives to educate people on the benefits of multimodal transport alternatives, supplemented by user-friendly technologies such as mobile travel planning apps, can increase acceptance and usage.

2 Methodology

This study utilizes a Geographic Information System based method to improve public transportation accessibility in Rawalpindi. The methodology summarizes the step-by-step procedure, concentrating on data collection, network analysis and multimodal integration to propose a sustainable and efficient transport network in the studied region as shown in Fig. 1.

2.1 Study area description

The study works on Rawalpindi, a fast growing city in Pakistan that assists as a critical centre for inter-city transportation and passenger traffic with its twin city, Islamabad. The designated area's public transportation system is reflected by limited integration and high traffic congestion, particularly in peri-urban zones. These routes connect to main transportation corridors, including Murree Road, Saddar often face severe congestion, influencing poorly on travel efficiency and accessibility. Also, the city's transport system is fragmented, with inadequate multimodal integration and limited coverage in peripheral areas. This situation required the use of GIS to analyse, optimize, and propose multimodal solutions for Rawalpindi's public transport network. Fig. 2 presents important information about the transport network of Pakistan including the study area, such as Fig. 2 (a) the road network of Pakistan Fig. 2 (b) road network of Rawalpindi city Fig. 2 (c) study area map Fig. 2 (d) pictorial diagram of the studied routes in the area, and Fig. 2 (e) Traffic condition in the study area. Spatial data such as road networks, satellite imagery, and bus stop locations were sourced from platforms like Google Earth and local municipal authorities.

2.2 Data collection

The initial phase involved collecting comprehensive datasets to create the base of the GIS-based study. Demographic data such as population density, socioeconomic profiles, and commuter demand patterns were obtained from the Pakistan

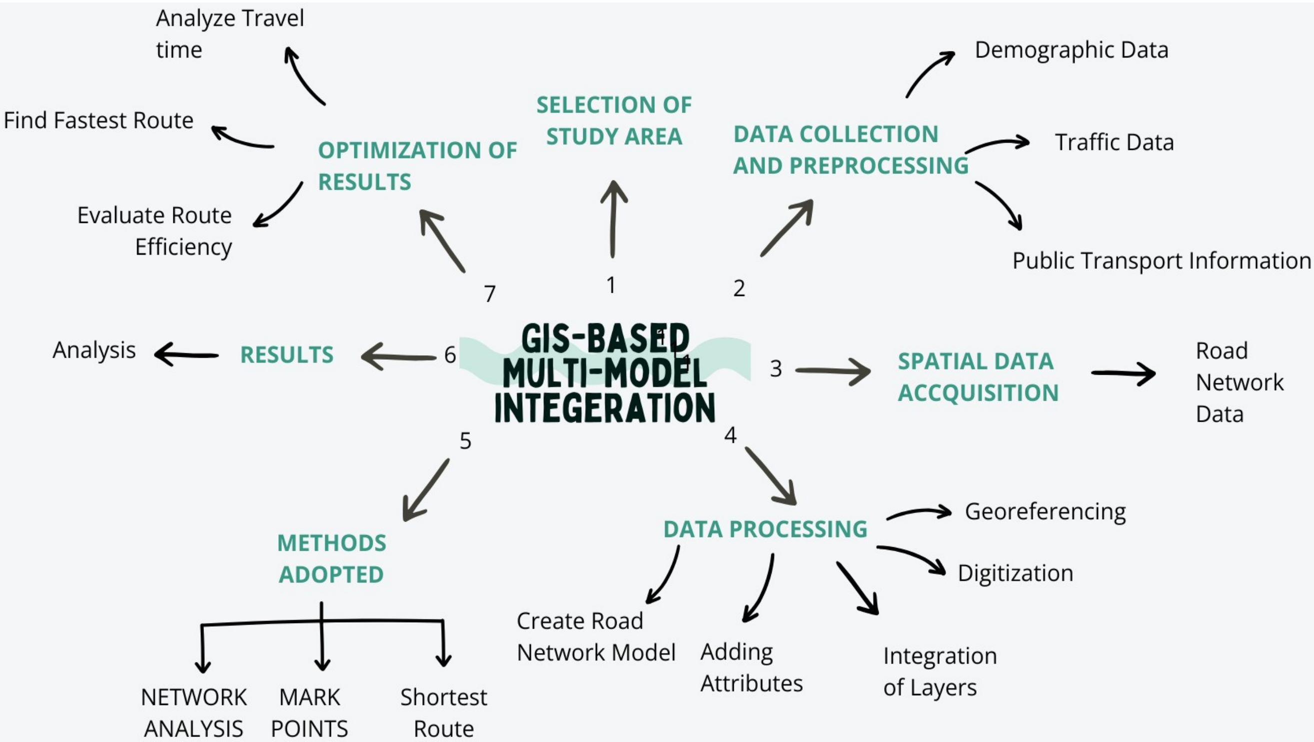

Fig. 1 Methodology flowchart

Bureau of Statistics as presented in Table 1. These datasets were critical in identifying areas with high mobility demands.

Table 2 shows important information regarding the traffic mix (type of vehicles operating in specified time periods) and traffic direction (one way or two way) for the observed routes of the study area.

Traffic volume data was collected through the use of a standardized traffic count form, which aided to systematically calculate the number of vehicles passing definite points during nominated intervals. The Civil engineering students from COMSATS University Islamabad, Wah Campus participated in data collection on specified routes at various key points. This study was part of their final year project. Tables 3 and 4 provide a thorough summary of the performance criterion for several traffic routes at the study area, focused on key parameters such as the Peak Hour Factor (PHF), Maximum Service Flow (MSF), Volume-to-Capacity (*V/C*) Ratio, and Level of Service (LOS). The PHF specifies the consistency of traffic flow during peak hours, with lower values signifying higher variability. The MSF describes the maximum traffic flow that can be assembled per lane for a specific LOS, decreasing as congestion worsens. The *V/C* ratio characterizes the roadway demand compared to its capacity, with values above 1.0 identifying oversaturated conditions. LOS categorizes traffic flow feature from free-flowing situations (LOS A) to worst congestion and interruption (LOS F). The measured results showed LOS E, and LOS F states for the studied routes, representing varying levels of congestion. The LOS F highlight situations where demand surpasses capacity, causing the substantial delays and traffic jam, highlighting the critical necessity for traffic management and capacity improvements in specified routes of the study area.

2.3 Spatial data acquisition

After data collection, spatial data layers were georeferenced to align with real geographic coordinates, considering prominent benchmarks such as intersections and bus terminals as control points. Accordingly, the road network was configured into vector layouts, and each road section was characterized by category (e.g., highways, arterial roads, and local streets). Features such as speed limits, and traffic density were allocated to each section. The position of bus stops, metro stations, and pedestrian paths were indicated as point layers within the GIS framework. This inclusive preparation endorsed for a smooth incorporation of datasets during the analysis period. Finally, the georeferenced layers were assimilated into a GIS environment, forming a cohesive basis for advanced analysis. The integration incorporated overlaying demographic data to identify high-demand zones.

The next stage involved producing a multimodal transportation network within the GIS base. This setup integrated buses, metro lines, and pedestrian paths, enabling smooth shifts between transport modes. Nodes in the network characterized intersections, bus stops, and metro

(a) (b) (c) (d) (e)

Fig. 2 (a) Road map of Pakistan (b) Road network of Rawalpindi (c) Study area routes (d) Study area map (e) Traffic situation in study area

stations, while edges corresponded to road segments and metro lines. The road network of Rawalpindi city was similarly modelled in GIS as shown in Fig. 3.

2.4 Network dataset creation

Attributes were allocated to the network modules, including travel time, length, congestion intensities, and pedestrian convenience. These features created the basis for computing efficient routes. By incorporating all important transport elements, the network provided a holistic illustration of the city's transportation network.

Dijkstra's algorithm, a commonly used shortest-path algorithm, was utilized to identify the most efficient routes (Noto and Sato, 2000). The algorithm reflected impedance factors such as travel time, traffic density, and speed limits to evaluate optimal paths. For example, congested intersections like

Table 1 Demographic overview of Rawalpindi city

Parameter	Value	Source
Total population	2.1 million	Pakistan Bureau of Statistics (2023)
Urban population (%)	75%	
Population growth Rate (%)	2.2% per annum	
Socioeconomic indicator	Middle-income group	
High-mobility demand areas	Murree Road, Saddar	Local traffic surveys

Table 2 Traffic classification and flow directions in the study area

Road name	Traffic type		Traffic direction
	(6 a.m. to 11 p.m.)	(11 p.m. to 6 a.m.)	
Marrir to Kacheri chowk	M.cycles, cars, jeeps, Light Transport Vehicles (LTV)	M.cycles, cars, jeeps, LTV, Heavy Transport Vehicles (HTV), trucks	One way
Kacheri chowk to Rawat	M.cycles, cars, jeeps, LTV	M.cycles, cars, jeeps, LTV, HTV, trucks	One way
Kacheri chowk to Bakra Mandi	M.cycles, cars, jeeps, LTV	M.cycles, cars, jeeps, LTV, HTV, trucks	Two way

Table 3 LOS of route 1 in the study area

From Rawat to Marir chowk				From Marir chowk to Rawat			
PHF	MSF	*V/C*	LOS	PHF	MSF	*V/C*	LOS
0.87	1,200	0.8	E	0.85	1,200	0.85	E

Table 4 LOS of route 2 in the study area

From Bakra mandi to Kacheri				From Kacheri to Bakra mandi			
PHF	MSF	*V/C*	LOS	PHF	MSF	*V/C*	LOS
0.70	900	1.20	F	0.75	1,000	1.3	F

Fig. 3 Junctions and edges of roads

Kacheri Chowk were allocated higher impedance values, inspiring the algorithm to highlight less congested alternatives. The model integrated real-time traffic data to improve route efficiency dynamically as presented in Fig. 4.

3 Results and discussion

This study results revealed serious insights into the existing state of public transportation in Rawalpindi, the efficiency of Geographic Information System (GIS)-based intrusions, and their prospective to improve the efficiency, accessibility, and sustainability of the city's transportation system. This section presents comprehensive findings, reinforced by quantitative and qualitative investigation, and discusses their consequences in the wider perspective of urban mobility challenges.

3.1 Route optimization

Route optimization was a significant part of the methodology, concentrating on improving the efficiency of specified routes in the study area. GIS tools were utilized to evaluate existing transport routes, detect inefficiencies, and propose optimized options. The optimization method evaluated the results such as proposed new routes, and additional BRT system on these routes to improve accessibility. This ensured equitable access to public transportation, particularly for low-income and underserved populations.

3.2 Shortest route (Rawat–Marrir Chowk)

The below shortest route as shown in Fig. 5 connects Rawat with the Marrir Chowk (Route 1). This considerably cuts the total travel distance, decrease congestion and results in improved physical and natural environment. By using ArcMap, the route is visually presented on a map alongside important geographical features, allowing planners to see the connection between transport routes and the adjacent situation. The screenshot from ArcMap shows a broad section of the route, marked by different colour points. The clear visualization aids in refining and validating the optimal routes produced during the network analysis stage.

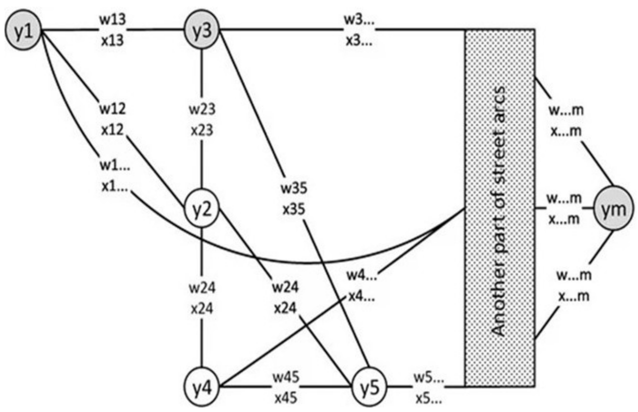

Fig. 4 Multi model (Dijkstra's algorithm)

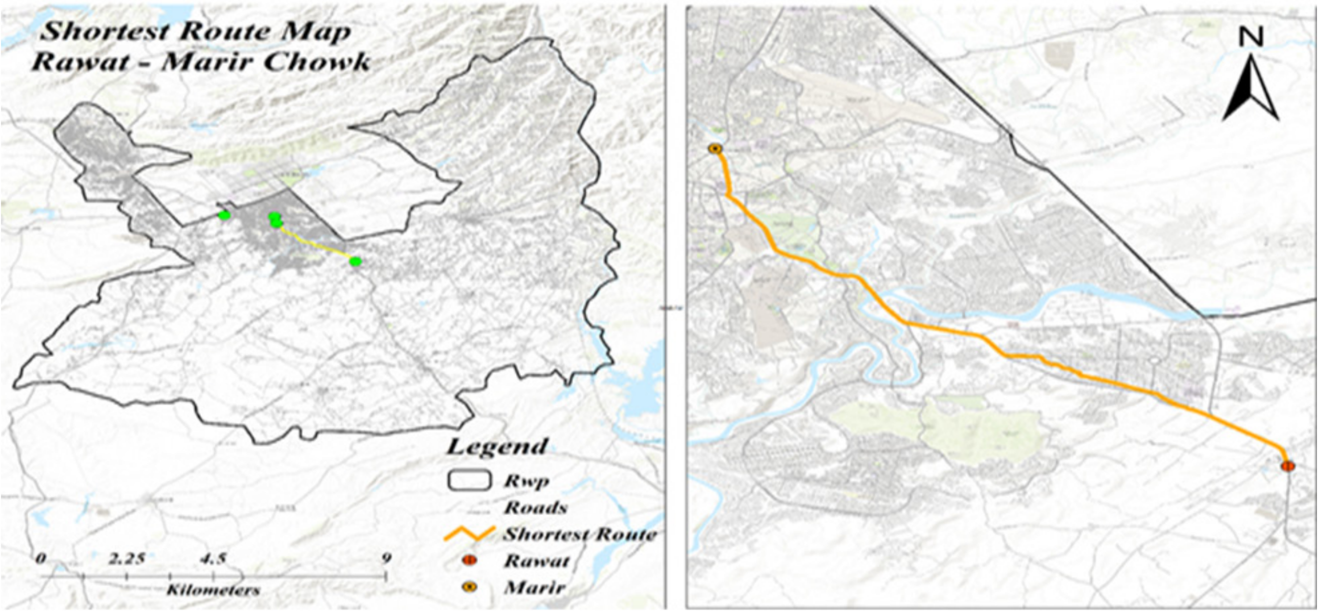

Fig. 5 Shortest route from Rawat to Marrir chowk

In addition, Table 5 presents the attribute table for the shortest route from Rawat to Marrir Chowk, as visualized in ArcMap. The attribute table presents important data points such as the total length in km of the route, estimated travel time in minutes, and road type for each segment.

This GIS generated data also helps in analysing the efficiency and probability of the proposed Bus Rapid Transit (BRT) route. The outcome of the analysis specifies that we can get more benefits from interchanging conventional transport systems with the metro system. After choosing the most efficient route, the BRT system as depicted in Fig. 6 can optimize bus scheduling and resource allocation. This can lead to higher ridership as passengers observe time savings and reliability. With a well-planned BRT route fewer cars might be on the road leading to uniform traffic flow. Reduced traffic congestion on Rawalpindi's roads is also a potential benefit.

3.3 Shortest route (Bakra Mandi–Kacheri Chowk)

The below shortest route as shown in Fig. 7 connects Bakra Mandi to Kacheri chowk (Route 2). These routes tend to serve the communities with a low cost, feasible and comfortable transportation service. The careful positioning of these stops forms smooth transit operations, composed with passenger convenience, facilitating effective boarding points while preserving optimal travel times across the route.

Table 6 provides the attribute values for the shortest route between Bakra Mandi and Kacheri Chowk, as measured and presented in the ArcMap. These attribute values includes important attributes such as the segment length in km, estimated travel time in minutes and road type.

After optimizing the shortest route between Bakra Mandi and Kacheri Chowk (Route 2), the BRT system was proposed in this route as depicted in Fig. 8, which can optimize bus scheduling and resource allocation. This step in the planning also considers future scalability, allowing for potential expansions as public transport demand grows over time.

3.4 Interconnected routes

Interconnected routes play a significant role in developing an integrated and efficient public transportation system by connecting separate bus routes, permitting passengers to transfer smoothly between them. In the context of this study, the two optimized BRT routes—Route 1 (Rawat to Marrir Chowk) and Route 2 (Bakra Mandi to Kacheri Chowk)—intersect at Kacheri Chowk, forming a network that tremendously improves connectivity across the study area.

This interconnected system allows passengers to travel longer distances through public transport without requiring private vehicles and transit points. For instance, passengers from Bakra Mandi can take Route 2 to Kacheri Chowk

Table 5 Attribute table for shortest route from Rawat to Marrir chowk

FID	Shape	Object ID	Name	Facility ID	Incident Cu	Facility Cu	Incident ID	Total Length	Total Time
0	Polyline M	1	1	Bakra Mandi-Kacheri Chowk	2	1	1	8.60023	9.316913

Fig. 6 BRT system on the shortest route

and then move to Route 1, which takes them further toward the central Marrir Chowk area or onto the metro system. This integration decreases travel time, congestion, and the requirement for multiple tickets or transport modes, promoting a more efficient transit experience.

Both of our shortest routes are integrated with each other at Kacheri Chowk point. Fig. 9 shows that a great area of Rawalpindi is covered by these routes and links the far points of the city with each other. Also, the route is linked with Marrir Chowk metro station which shows a high approach for the citizens to the main Islamabad city. This will further help passengers to experience significantly reduced travel times, mainly during rush hour, thanks to allocated lanes that bypass traffic congestion.

Additionally, interconnected routes enhance service reliability and flexibility. In case of disorders or delays on one route, passengers can comfortably shift to alternate routes, ensuring smooth travel. This system design also aids to disperse passenger loads across different sections of the network, decreasing overcrowding during peak hours and facilitating a more balanced and sustainable public transport infrastructure. Similarly, a study conducted in Singapore, researchers utilized GIS tools to optimize bus routes, concentrating on improving commuter accessibility and decreasing travel times. The results revealed a 20% reduction in average commute durations, with 95% of the population finding access to bus stops within a 500-meter distance. Another study conducted in New York City applied GIS-based accessibility analysis to optimize the placement of new transit stops. The study results revealed a significant development in transit equity, with underserved populations acquiring better access to public transport within a 15-minute walking distance (Madhu et al., 2023; de Palma and Picard, 2005). This study considered the potential of GIS to dynamically optimize the specified routes in the study area based on real-time traffic data, thereby decreasing delays and improving operational efficiency.

4 Conclusions

Optimization of highly congested routes was a significant aim of this study. By incorporating real-time traffic data into the GIS model, the analysis provided insights into congestion configurations and prospective solutions.

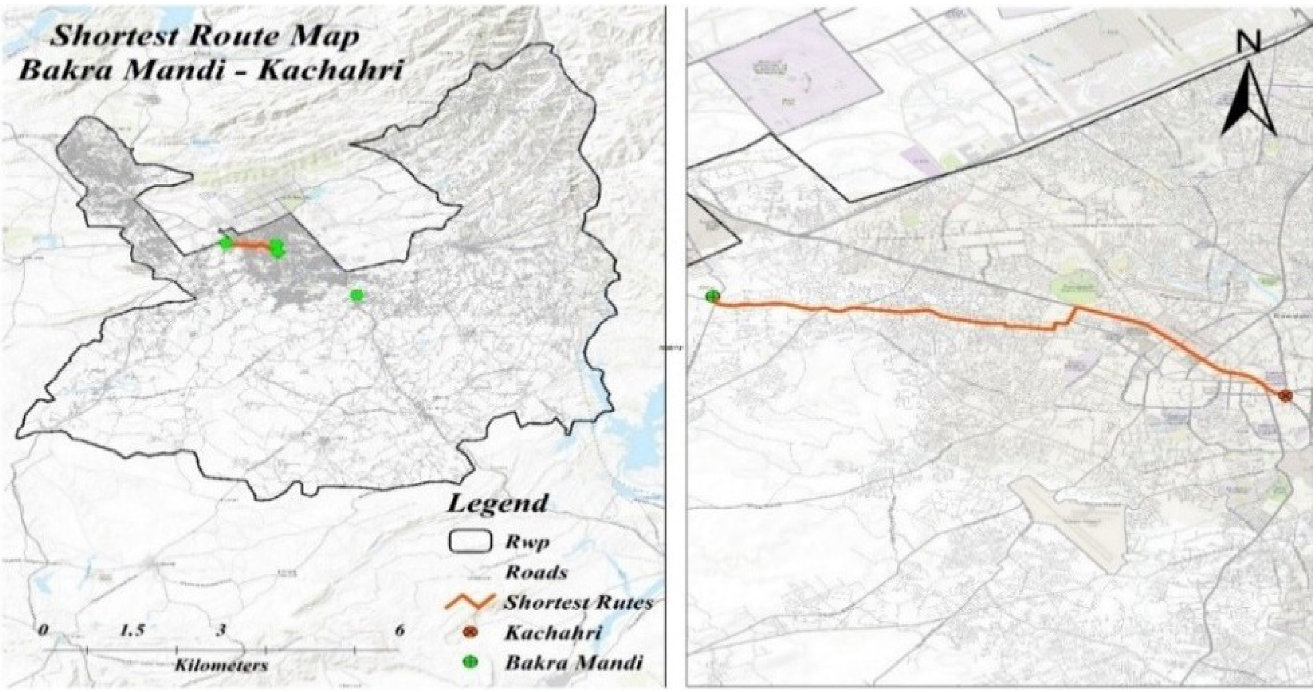

Fig. 7 Shortest path from Bakra Mandi to Kacheri chowk

Table 6 Attribute table for shortest path from Bakra Mandi– Kacheri Chowk

FID	Shape	Object ID	Facility ID	Name	Incident Cu	Facility Cu	Incident ID	Total Length	Total Time
0	Polyline M	4	3	Rawat-Marir Chowk	2	1	1	18.671795	17.235507

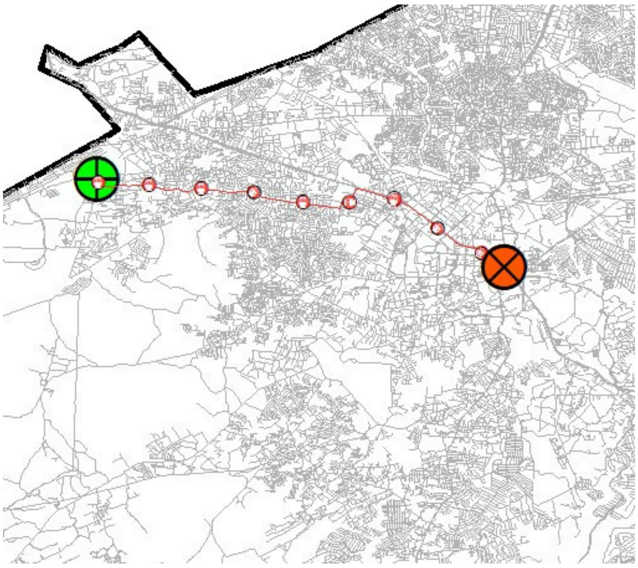

Fig. 8 BRT system on the shortest route

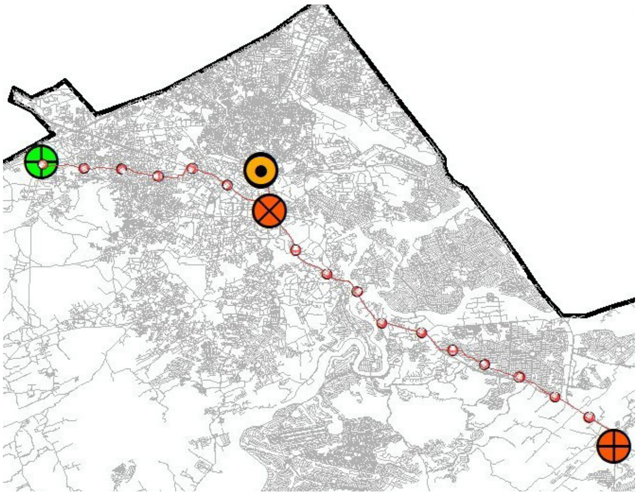

Fig. 9 Interconnecting routes in the study area

GIS based maps presented performance metrics such as reduced travel times, enhanced accessibility scores, and better public transport usage. These metrics were critical for validating the proposed solutions and ensuring their feasibility for implementation. LOS results revealed the worst (E and F) operating conditions of specified routes in the study area. While the proposition of BRT system in the optimized routes itself becomes more efficient, leading to increased ridership as travellers switch from cars. This not only decreases operational costs but also represents a step towards a greener city. With fewer cars on the road, air pollution from emissions declines, improving public health.

The incorporation of GIS in Rawalpindi's public transportation planning also requires investments in infrastructure and capacity building. Training programs for transportation authorities and urban planners to efficiently use GIS tools are essential for sustaining long-term developments. The application of pilot projects in high-traffic corridors could help as a proof of concept, proving the noticeable benefits of GIS-based systems and building stakeholder confidence in rising these solutions city-wide.

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