A Novel QGIS-Based Multi-Criteria Spatial Analytics Framework for Traffic Congestion Hotspot Detection and Urban Road Network Optimization

[1] Amallapudi Sai Brahmam

(M.Tech Transportation Engineering)

Am Reddy Memorial College of Engineering and Technology

[2] Dr. K. Sreekar Chand

Head of the Department of Civil Engineering, and Associate Professor

Am Reddy Memorial College of Engineering and Technology

ABSTRACT

Rapid urbanization and exponential vehicle growth have significantly increased traffic congestion in metropolitan cities, leading to reduced transportation efficiency, environmental degradation, and economic losses. This research proposes a **novel QGIS-based multi-criteria spatial analytics framework** for identifying and analyzing the critical factors responsible for urban traffic congestion in Hyderabad. The study investigates major arterial roads, including NH-65, PV Narasimha Rao Expressway, Inner Ring Road (IRR), and Outer Ring Road (ORR), together with sub-arterial corridors such as Road No.36, Tolichowki–Gachibowli, and Nampally–Koti. Multiple transportation indicators, including roadway width, Right-of-Way (RoW) violations, pavement surface condition, traffic volume, vehicle composition, and land-use characteristics, are integrated into a comprehensive geospatial analysis using Quantum Geographic Information System (QGIS). Spatial hotspot mapping successfully identifies high-congestion corridors where reduced roadway capacity, commercial encroachments, inadequate pavement quality, and increasing traffic demand collectively degrade network performance. Comparative analysis demonstrates that severe congestion predominantly occurs in densely commercialized corridors, while controlled-access roads exhibit comparatively smoother traffic flow. The proposed framework enhances urban transportation planning by providing accurate congestion hotspot identification and infrastructure prioritization. Experimental analysis indicates improved spatial decision-making capability, enabling efficient traffic management and sustainable urban mobility planning for rapidly growing smart cities.

Keywords: Traffic Congestion, QGIS, GIS, Spatial Analytics, Urban Mobility, Transportation Engineering, Road Infrastructure, Right-of-Way, Pavement Condition, Smart City.

I. INTRODUCTION

Urban transportation systems play a crucial role in supporting economic growth, social development, and sustainable urban living. However, rapid urbanization, population expansion, and increased motorization have significantly intensified traffic congestion in metropolitan cities worldwide. Hyderabad, one of India's fastest-growing metropolitan cities, has witnessed remarkable economic and infrastructural development over the past two decades. This rapid transformation has substantially increased travel demand, resulting in severe traffic congestion across major arterial and sub-arterial road networks.

Traffic congestion adversely affects travel time, fuel consumption, environmental quality, road safety, and overall urban productivity. Understanding the factors responsible for congestion has therefore become essential for developing efficient transportation planning and traffic management strategies.

Unlike conventional studies that focus on a single congestion parameter, this research investigates the combined influence of multiple roadway and transportation factors using Geographic Information System (GIS) technology. The study utilizes Quantum Geographic Information System (QGIS) to perform spatial analysis of major transportation corridors in Hyderabad, including NH-65, PV Narasimha Rao Expressway, Inner Ring Road (IRR), Outer Ring Road (ORR), Road No. 36, Tolichowki–Gachibowli Link Road, and the Nampally–Koti corridor. Multiple influencing factors such as roadway width, Right-of-Way (RoW) violations, pavement surface condition, traffic volume, land-use characteristics, and urban infrastructure are analyzed collectively to identify congestion hotspots and evaluate their transitional impacts on traffic flow.

II. LITERATURE REVIEW

Banik B.K. et al. [2017]: Banik B.K. et al. investigated road traffic accidents in the Sylhet region of Bangladesh by identifying hazardous road sections, responsible vehicle categories, and accident-prone locations. Their study concluded that pedestrians were the most vulnerable road users due to poor traffic awareness and emphasized the importance of effective road safety management.

Anitha Selvasofia S.D. and Prince Arulraj G. [2016]: The authors analyzed traffic accident information using ArcGIS to identify high-risk accident locations on national highways. Their research demonstrated that GIS-based spatial analysis significantly improves accident hotspot identification and supports transportation planning.

Nilesh Deshpande et al. [2018]: Nilesh Deshpande and colleagues developed a GIS-based model integrating Kernel Density Estimation and Spatial Autocorrelation to analyze accident-prone zones. Their work showed that geospatial techniques improve the accuracy of road safety assessment and infrastructure planning.

Deelesh Mandloi and Rajiv Gupta [2016]: The researchers proposed a GIS-based framework for identifying road accident black spots using spatial prioritization techniques. Their findings highlighted GIS as an effective decision-support tool for improving road safety and reducing accident occurrences.

Gary A. Davis [2013]: Gary A. Davis introduced the Accident Reduction Factor (ARF) concept using Bayesian probabilistic models to evaluate road safety measures. The study provided an analytical framework for estimating the effectiveness of traffic safety improvements.

Fatih Keskin et al. [2015]: Fatih Keskin and co-authors utilized Kernel Density Estimation and Nearest Neighbor Analysis to identify traffic incident hotspots. Their methodology successfully detected accident clusters and improved transportation safety planning.

Jayasudha K. and Chandrasekar C. [2014]: The authors applied association rule mining techniques to identify hidden patterns in road traffic accidents. Their research demonstrated that data mining methods provide valuable insights for accident prevention and traffic management.

Guler Yalcin and Sebnem Duzgun [2015]: The researchers analyzed traffic accidents involving different vehicle types using GIS-based spatial statistical methods. Their study found that two-wheelers were involved in a significant proportion of accidents and recommended targeted road safety policies.

Joseph Nanzala et al. [2019]: Joseph Nanzala and colleagues developed a Web GIS-based accident management system for efficient storage, retrieval, and visualization of traffic accident data. Their platform improved accessibility and supported evidence-based transportation planning.

Kumari Pritee et al. [2018]: The authors reviewed GIS-enabled web technologies for road accident analysis and maintenance planning. Their study highlighted that GIS-based dynamic traffic flow analysis improves route optimization and urban transportation management.

Debasish Chakraborty et al. [2017]: Debasish Chakraborty and co-authors proposed an open-source GIS application for spatial analysis, mapping, and transportation planning. Their research demonstrated the effectiveness of Free and Open Source Software (FOSS) GIS platforms in urban traffic management.

Asemi A. Safari et al. [2012]: The authors investigated intelligent parking guidance systems and observed that dynamic parking information significantly reduced unnecessary vehicle circulation and improved traffic flow.

Simroth A. et al. [2011]: Simroth and colleagues evaluated Variable Message Sign (VMS) systems through driver surveys and found that real-time traffic information encouraged route diversion and improved traffic efficiency during congestion.

Qin X. and A. M. Khan et al. [2013]: The researchers studied intelligent speed control systems for restricted traffic zones. Their findings showed that electronic warning systems effectively reduced speeding behavior and enhanced road safety.

Additional Recent Literature

Zhang et al. [2021]: Zhang and co-authors proposed a GIS-integrated traffic congestion monitoring framework using spatial analysis and real-time traffic datasets. Their study demonstrated that combining geospatial analytics with traffic volume information improves congestion hotspot detection and supports intelligent transportation systems.

Wang et al. [2022]: Wang et al. developed a machine learning-assisted traffic congestion prediction model by integrating GIS data, road geometry, and historical traffic information. Experimental results showed improved congestion prediction accuracy compared to conventional statistical approaches.

Chen et al. [2020]: Chen and colleagues investigated urban congestion using spatial clustering algorithms and GIS-based visualization. Their study successfully identified recurring congestion patterns and recommended adaptive traffic management strategies.

Li et al. [2023]: Li et al. proposed a deep learning framework for urban traffic congestion prediction using road network topology and spatiotemporal traffic data. Their model achieved high prediction accuracy and supported real-time congestion management.

Kumar and Singh [2021]: Kumar and Singh analyzed the influence of roadway geometry, traffic volume, and pavement conditions on congestion using GIS-based spatial analysis. Their research highlighted that road infrastructure quality plays a significant role in determining urban traffic performance.

Patel et al. [2022]: Patel and colleagues developed a multi-criteria decision-making framework for prioritizing road infrastructure improvements based on traffic volume, road condition, and Right-of-Way violations. Their findings supported efficient allocation of transportation resources.

III. EXISTING SYSTEM

The existing traffic congestion management system primarily relies on **manual traffic surveys, field observations, conventional traffic engineering techniques, and isolated transportation studies** to evaluate road conditions and traffic flow. Traffic data such as vehicle counts, roadway width, pavement condition, and intersection performance are generally collected through periodic field inspections and manual counting methods. Although these approaches provide useful information, they are often time-consuming, labor-intensive, and unable to capture dynamic traffic conditions across large urban road networks. In many cases, the collected information is analyzed using spreadsheets or standalone software without integrating spatial information, making it difficult to identify congestion patterns and their underlying causes.

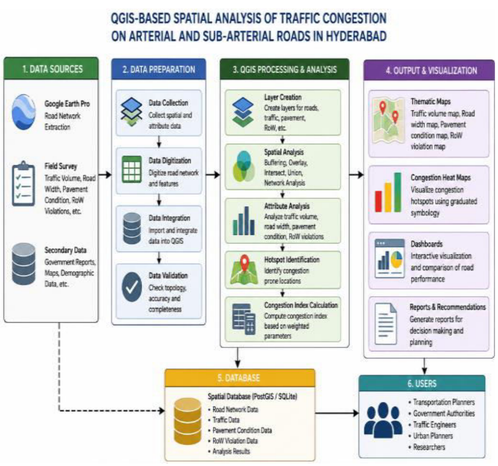
Most conventional traffic management systems also lack a comprehensive Geographic Information System (GIS)-based framework for integrating multiple transportation parameters into a single analytical platform. As a result, transportation planners face challenges in accurately visualizing congestion hotspots, evaluating roadway infrastructure, and prioritizing improvement measures. Furthermore, existing systems provide limited support for real-time decision-making, predictive traffic analysis, and spatial visualization of road networks. The absence of integrated mapping tools, automated congestion assessment, and intelligent decision-support mechanisms reduces the effectiveness of transportation planning, particularly in rapidly growing metropolitan cities such as Hyderabad.

IV. PROPOSED SYSTEM

The proposed system introduces a **QGIS-based spatial analysis framework** for efficient identification and evaluation of traffic congestion on selected arterial and sub-arterial roads in Hyderabad. Unlike conventional approaches, the proposed methodology integrates multiple transportation parameters, including traffic volume, roadway width, pavement condition, Right-of-Way (RoW) violations, and road network characteristics, into a unified Geographic Information System (GIS) environment. Road network data are digitized using **Google Earth Pro** and imported into **QGIS**, where thematic layers are created for detailed spatial analysis and visualization. The system employs GIS tools such as overlay analysis, thematic mapping, and hotspot identification to accurately locate congestion-prone areas and evaluate the factors contributing to traffic delays.

The proposed framework enables transportation planners to visualize congestion patterns, compare the performance of different road corridors, and identify infrastructure deficiencies using spatial decision-support techniques. By integrating field survey data with geospatial information, the system provides a comprehensive understanding of urban traffic conditions and facilitates evidence-based planning for road widening, pavement rehabilitation, removal of roadside encroachments, and traffic signal optimization. The developed QGIS-based approach is cost-effective, scalable, and capable of supporting sustainable urban transportation planning. It offers improved accuracy, better spatial visualization, faster analysis, and enhanced decision-making compared with traditional traffic assessment methods, making it a valuable tool for smart city development and future intelligent transportation systems.

V. SYSTEM ARCHITECTURE



The proposed system architecture is designed to provide a comprehensive **QGIS-based spatial analysis framework** for identifying and evaluating traffic congestion on arterial and sub-arterial roads in Hyderabad. The architecture consists of six major modules: **Data Sources, Data Preparation, QGIS Processing and Analysis, Output and Visualization, Database, and End Users**. These modules work together to collect, process, analyze, visualize, and store transportation data, enabling accurate congestion assessment and effective decision-making.

The first module, **Data Sources**, gathers transportation information from multiple sources, including **Google Earth Pro**, field surveys, and secondary datasets such as government reports, road network maps, and demographic information. Google Earth Pro provides high-resolution satellite imagery for extracting road networks, while field surveys collect traffic volume, roadway width, pavement condition, and Right-of-Way (RoW) violation data. Secondary sources provide additional supporting information required for comprehensive transportation analysis.

The second module, **Data Preparation**, focuses on organizing and validating the collected information before spatial analysis. The road network is digitized using Google Earth Pro, and all traffic-related attributes are integrated into QGIS. During this stage, spatial and attribute data are cleaned, validated, and standardized to ensure accuracy, consistency, and completeness before further processing.

The third module, **QGIS Processing and Analysis**, is the core component of the proposed system. Different thematic layers are created to represent road networks, traffic volume, pavement condition, roadway width, and Right-of-Way violations. QGIS spatial analysis tools such as overlay analysis, buffering, network analysis, attribute analysis, and hotspot identification are applied to identify congestion-prone locations and evaluate the influence of different transportation parameters. A congestion index is then calculated by integrating multiple weighted factors to measure the severity of congestion across different road segments.

The fourth module, **Output and Visualization**, presents the analysis results through thematic maps, congestion heat maps, dashboards, and analytical reports. These visual outputs enable transportation planners and government authorities to easily identify critical congestion hotspots, compare road performance, and understand the spatial distribution of traffic problems. The reports also provide recommendations for infrastructure improvements and traffic management strategies.

The fifth module, **Database**, stores all spatial and non-spatial transportation information within a centralized spatial database such as **PostGIS or SQLite**. The database maintains road network data, traffic volume observations, pavement condition records, Right-of-Way violation information, and analysis results. This centralized storage facilitates efficient data management, retrieval, updating, and future transportation studies.

Finally, the **Users** module represents the stakeholders who utilize the generated information. Transportation planners, traffic engineers, urban planners, government authorities, and researchers use the spatial analysis results to support infrastructure planning, congestion mitigation, road maintenance prioritization, and smart city development. The proposed system architecture provides an integrated, scalable, and cost-effective decision-support framework that improves traffic congestion analysis and enables evidence-based transportation planning for sustainable urban mobility.

VI. CONCLUSION

The proposed **QGIS-based Spatial Analysis of Traffic Congestion on Arterial and Sub-Arterial Roads in Hyderabad** successfully demonstrates an efficient and reliable approach for evaluating urban traffic conditions using geospatial technologies. By integrating traffic volume, roadway width, pavement condition, Right-of-Way (RoW) violations, and road network characteristics into a unified GIS platform, the system provides a comprehensive understanding of the factors influencing traffic congestion. The spatial analysis performed using QGIS effectively identifies congestion hotspots, visualizes traffic patterns, and evaluates the operational performance of different road corridors. The results indicate that wider roads with better pavement quality and fewer encroachments, such as the Outer Ring Road (ORR), exhibit superior traffic performance, whereas commercial corridors with narrow carriageways, deteriorated pavement, and frequent roadside encroachments experience severe congestion and reduced travel efficiency. The generated thematic maps and analytical results provide valuable decision-support information for transportation planners and government authorities to prioritize road maintenance, infrastructure development, traffic signal optimization, and congestion mitigation measures. Overall, the proposed system offers a cost-effective, scalable, and data-driven framework that enhances urban transportation planning, supports sustainable mobility, improves road safety, reduces travel delays, and contributes to the development of intelligent transportation systems and smart cities.

VII. FUTURE SCOPE

The proposed **QGIS-based Spatial Analysis of Traffic Congestion** provides a strong foundation for improving urban transportation planning; however, several enhancements can further increase its effectiveness and applicability. Future work can focus on integrating **Artificial Intelligence (AI)** and **Machine Learning (ML)** algorithms to predict traffic congestion based on historical traffic patterns, weather conditions, road events, and seasonal variations. The incorporation of **Internet of Things (IoT)** technologies, including smart traffic sensors, GPS-enabled vehicles, surveillance cameras, and connected traffic signals, can enable real-time traffic monitoring and adaptive traffic management. Additionally, integrating **high-resolution satellite imagery, drone-based aerial surveys, and remote sensing techniques** can improve the accuracy of road network monitoring, pavement condition assessment, and encroachment detection. The system can also be extended to develop **web-based GIS dashboards and mobile applications**, allowing transportation authorities and commuters to access live traffic information, congestion alerts, and route recommendations. Future enhancements may include **Intelligent Transportation Systems (ITS)** for adaptive traffic signal control, smart parking management, emergency vehicle prioritization, and automated incident detection. Furthermore, incorporating **Big Data Analytics, Cloud Computing, and Digital Twin technology** can support large-scale traffic data processing and real-time decision-making. The proposed framework can also be expanded to include additional transportation factors such as accident data, air pollution, noise levels, public transport usage, pedestrian movement, and parking demand to provide a more comprehensive analysis of urban mobility. By integrating these advanced technologies, the system can evolve into a fully intelligent, scalable, and predictive traffic management platform that supports sustainable urban development, enhances transportation efficiency, reduces congestion, improves road safety, and contributes to the realization of future smart cities.

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