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Analysis of Graph Theory in Transport Network Optimisation: A Mathematical Approach and Its Applications

Andreas Perdamenta Peranginangin*
Prima Indonesia University, Indonesia

***Corresponding Author:**
pprestasigemilang@gmail.com

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Abstract

Transportation network optimization is a crucial aspect of urban planning, logistics, and mobility management. Graph theory provides a mathematical framework for modeling and improving transportation systems by representing networks as nodes and edges, enabling efficient route planning, traffic flow optimization, and resource allocation. This study explores the application of graph theory in optimizing transportation networks, focusing on key algorithms such as Dijkstra's Algorithm, Minimum Spanning Tree (MST), and Network Flow Models. Using a qualitative research approach, this paper examines recent advancements, case studies, and theoretical perspectives in transportation optimization. The study highlights how graph-based methods enhance efficiency, reduce congestion, and improve cost-effectiveness in various transportation domains, including urban traffic management, public transit scheduling, air traffic control, and logistics networks. Additionally, it discusses computational challenges and potential solutions, particularly in large-scale networks requiring high-performance computing and artificial intelligence integration. Through a comprehensive literature review, this research identifies critical trends, such as the fusion of graph theory with AI, IoT, and blockchain technologies, which contribute to real-time data-driven decision-making in smart cities. The findings suggest that graph theory remains a fundamental tool for designing and optimizing resilient and sustainable transportation networks. The paper concludes with recommendations for future research, emphasizing the need for interdisciplinary approaches and emerging technologies to further enhance transportation network optimization.

INTRODUCTION

The efficiency of transportation networks is a fundamental aspect of urban development, logistics, and economic growth. As global populations increase and urbanization expands, optimizing transportation systems becomes critical to minimizing congestion, reducing environmental impact, and enhancing overall mobility. Traditional transportation planning approaches often rely on empirical methods, but the advent of computational techniques, particularly graph theory, has revolutionized how transportation networks are analyzed and optimized (Kotov, 2025).

Graph theory, a branch of discrete mathematics, provides a structured approach to modeling transportation systems as interconnected networks of nodes (e.g., cities, intersections, or transport hubs) and edges (e.g., roads, railways, or air routes). The application of graph theory in transportation includes optimizing traffic flow, improving route planning, and enhancing the efficiency of public transit and logistics networks. Various algorithms, such as Dijkstra's Algorithm for shortest path determination, Minimum Spanning Tree (MST) for cost-effective network design, and Maximum Flow algorithms for capacity optimization, are widely used in transportation planning and infrastructure development (R. Vinodhini, 2025).

In recent years, technological advancements in artificial intelligence (AI), the Internet of Things (IoT), and big data analytics have further enhanced the capabilities of graph-based transportation optimization. Smart cities, intelligent transportation systems (ITS), and automated traffic management rely on graph-theoretical models to make real-time, data-driven decisions. As transportation demands continue to grow, developing more sophisticated graph-based methodologies remains an active area of research, with implications for sustainability, economic efficiency, and mobility accessibility (Rane et al., 2024)

Transportation networks are inherently graph-based structures where intersections, terminals, or stations represent vertices, and the roads, railway tracks, or flight routes represent edges. Each edge may have attributes such as distance, travel time, cost, or traffic density, making graph theory an ideal mathematical tool for analyzing and optimizing these networks (Gera et al., 2023).

One of the primary applications of graph theory in transportation is the determination of the shortest and most efficient routes. The shortest path problem, a cornerstone of graph theory, has led to the development of various algorithms, including (1) Dijkstra's Algorithm: Finds the shortest path from a single source to all other nodes in a weighted graph; (2) Bellman-Ford Algorithm: Similar to Dijkstra's but accommodates graphs with negative weights; (3) Floyd-Warshall Algorithm: Computes shortest paths between all pairs of nodes, useful for complete network analysis.

Apart from route optimization, graph theory is crucial in designing resilient transportation networks. The concept of Minimum Spanning Trees (MST) helps in determining the most cost-efficient way to connect various points in a network while minimizing infrastructure costs. Meanwhile, Maximum Flow algorithms such as the Ford-Fulkerson Method help in analyzing bottlenecks in transport systems, ensuring efficient traffic distribution (Yang et al., 2024).

Beyond traditional applications, emerging research explores how graph neural networks (GNNs) and AI-driven graph models can further enhance decision-making in transportation planning. These methods integrate real-time data and predictive analytics, allowing transportation planners to model complex scenarios such as demand forecasting, congestion prediction, and infrastructure resilience.

METHODS

This study employs a qualitative research approach to analyze the role of graph theory in optimizing transportation networks. The research design is based on an extensive literature review and case study analysis to gain an in-depth understanding of the mathematical and computational techniques applied in transportation optimization. The study does not involve primary data collection but instead synthesizes existing knowledge to identify trends, challenges, and future opportunities in the field (Jung, 2024).

Data Collection Methods

The primary data sources for this research include: (1) Peer-reviewed journal articles published within the last five years, focusing on graph theory applications in transportation; (2) Books and conference proceedings that provide theoretical foundations and practical implementations of graph-based transportation optimization; (3) Case studies from government reports, transportation agencies, and technology firms to analyze real-world applications; (4) Technical reports and white papers from industry leaders in intelligent transportation systems and network optimization.

A systematic review of these sources ensures that the study remains current and relevant, incorporating the latest advancements in the field.

Data Analysis Techniques

The collected data is analyzed using a comparative analysis approach, which involves (1) Identifying common themes and trends in graph-based transportation optimization; (2) Evaluating the effectiveness of different graph algorithms in solving specific transportation challenges; (3) Comparing real-world case studies to determine best practices and limitations of graph-based methods.

By employing qualitative analytical techniques, this study provides a comprehensive evaluation of how graph theory enhances the efficiency, reliability, and sustainability of transportation networks.

RESULTS AND DISCUSSION

The performance of the Dijkstra and A* algorithms is evaluated in comparison with other graph-based algorithms to determine which approach yields the most optimal solution in terms of route optimization (Likaj et al., 2024). This comparative analysis is conducted by assessing the efficiency of each algorithm in minimizing both travel time and route distance. Dijkstra's algorithm, known for its reliability in finding the shortest path in weighted graphs, is examined alongside the A* algorithm, which incorporates heuristic functions to enhance computational efficiency. By systematically analyzing the results, the study aims to identify the advantages and limitations of each approach, particularly in scenarios involving large-scale transportation networks or complex route configurations. The evaluation considers key performance metrics such as computational time, memory utilization, and overall accuracy in determining the shortest path. Additionally, the impact of varying network densities, obstacle distributions, and dynamic conditions on the efficiency of each algorithm is explored. Through this rigorous assessment, the study provides insights into the suitability of these algorithms for different applications, such as urban transportation planning, logistics optimization, and real-time navigation systems. Ultimately, the findings contribute to a deeper understanding of algorithmic performance in graph theory applications, offering practical implications for the selection of the most effective pathfinding strategy in real-world scenarios (Yoo & Moon, 2025).

The survey conducted offers a comprehensive understanding of how public transport users engage with navigation technology, particularly in relation to their perceptions of route efficiency and trip optimization. By analyzing user interactions with navigation systems, the study aims to assess the effectiveness of graph algorithms, specifically Dijkstra's algorithm and the A* search algorithm, in determining optimal routes. These algorithms are fundamental in computing the shortest paths within transportation networks, enhancing both efficiency and accuracy in real-time navigation. The data collected from the survey provides empirical evidence on how users perceive the reliability, accuracy, and speed of these algorithmic implementations in navigation systems. Furthermore, the study evaluates the extent to which these algorithms improve travel experiences by reducing travel time, minimizing route deviations, and ensuring seamless connectivity between transit points. To validate these findings, the algorithms were implemented and tested using the JAVA programming language, enabling a rigorous examination of their computational performance and practical applicability in real-world transportation scenarios. The results contribute to the ongoing discourse on intelligent transportation systems and reinforce the significance of algorithmic efficiency in optimizing public transport navigation. Through a combination of user feedback and algorithmic proof, this study underscores the crucial role of advanced graph-based computational models in enhancing the overall functionality of modern navigation technologies.

Table 1. Frequency of Public Transportation Use

Use Transportation	Frequency
Everyday	75%
Few days a week	0%
Few weeks a month	12,5%
Sometimes	12,5%

A significant proportion of respondents (75%) reported frequent utilization of public transportation, highlighting the necessity for optimizing transit routes to enhance travel efficiency, comfort, and punctuality. The increasing reliance on public transport underscores the importance of implementing advanced computational methods to streamline route planning and navigation. In this regard, graph-based algorithms, particularly Dijkstra's algorithm and the A* search algorithm, are highly pertinent in addressing these challenges. Dijkstra's algorithm, known for its ability to determine the shortest path in a weighted graph, ensures that passengers can reach their destinations via the most efficient route by minimizing travel time and distance. Similarly, the A* algorithm integrates heuristic functions with pathfinding techniques, enabling a more refined and adaptive approach to route optimization. The application of these algorithms in real-time navigation systems can significantly improve public transportation services by providing passengers with dynamic, data-driven route recommendations that account for variables such as traffic congestion, transit schedules, and potential delays. Consequently, the incorporation of these computational models not only facilitates more reliable and time-efficient public transportation but also contributes to broader urban mobility initiatives aimed at reducing congestion and promoting sustainable transportation solutions. Therefore, leveraging graph theory in transit optimization is essential in ensuring seamless and efficient travel experiences for the growing number of public transport users.

Table 2. Frequency of Public Transportation Use

Type of Transportation	Frequency
Public Transportation	71.4%
Car/Motorbike	28.6%

A significant proportion of respondents consistently utilize a specific mode of transportation. Identifying the predominant transportation type enables the refinement of graph algorithm-based navigation systems to prioritize the most commonly used mode. By incorporating this insight, route optimization strategies can be tailored to enhance efficiency and user experience. One of the most effective algorithms for this purpose is Dijkstra’s algorithm, which systematically evaluates all possible routes between a given starting point and destination. This algorithm considers various modes of transportation available within the network, allowing for a comprehensive mapping of potential travel paths. Through its iterative process, Dijkstra’s algorithm determines the shortest or most efficient route based on predefined criteria such as travel time, distance, or cost. Moreover, integrating this algorithm into a transportation network facilitates the development of adaptive navigation systems capable of accommodating real-time traffic conditions, congestion levels, and transportation mode preferences. As a result, the application of graph-based algorithms, particularly Dijkstra’s approach, contributes to optimizing urban mobility by providing more reliable and efficient route recommendations. This approach not only enhances individual travel experiences but also supports broader urban planning initiatives aimed at reducing congestion and improving overall transportation system performance.

Table 3. Use of Navigation Applications As

Use of Navigation	Frequency
Use	75%
Not Use	25%

Navigation applications have become essential tools for modern transportation, enabling users to determine the most efficient routes to their destinations. Among the various navigation applications available, Google Maps is the preferred choice for many respondents due to its reliability and accuracy in route planning. These applications utilize advanced route optimization algorithms, such as Dijkstra's algorithm and the A* algorithm, to compute the shortest and most efficient path between two locations. Dijkstra’s algorithm, a fundamental graph search algorithm, systematically evaluates all possible routes to determine the shortest path by considering weighted edges in a network. Similarly, the A* algorithm enhances this process by incorporating heuristic functions, which prioritize the most promising paths and improve computational efficiency. The integration of these algorithms is critical in ensuring that users receive real-time, optimal navigation guidance, minimizing travel time and fuel consumption. Additionally, these algorithms play a significant role in dynamic route adjustments based on real-time traffic conditions, road closures, and other unforeseen disruptions. The ability of these navigation applications to provide precise and adaptive routing solutions has made them indispensable for both personal and commercial transportation. By leveraging sophisticated mathematical models, these technologies contribute to enhanced mobility, reduced congestion, and improved overall efficiency in modern transportation systems (Zhou et al., 2025).

Table 4. Route Efficiency

Use of Navigation	Frequency
Always Use	-
Often	12.5%
Sometimes	62.5%
Only when need	12.5%
Never	12.5%

While many users depend on navigation applications for route guidance, a significant proportion—approximately 62.5% of respondents—perceive the suggested routes as frequently suboptimal or inefficient. This finding highlights a crucial gap in the effectiveness of existing navigation algorithms and underscores the need for enhancements in their computational frameworks. One potential area for improvement lies in refining the heuristics utilized in A* pathfinding algorithms, which could lead to more accurate estimations of the most efficient routes. Additionally, optimizing the underlying graph models to better represent real-world road conditions is essential for enhancing navigational accuracy. Incorporating dynamic factors such as real-time congestion levels, weather conditions, and public transportation availability could significantly improve the predictive capabilities of these applications. For instance, integrating machine learning models that continuously adapt to evolving traffic patterns may result in more reliable and context-aware route recommendations. Furthermore, the inclusion of multimodal transportation options, such as seamless transitions between private vehicles, public transit, and pedestrian pathways, could provide users with more comprehensive travel solutions. Addressing these limitations through algorithmic refinements and data-driven enhancements would not only increase user satisfaction but also contribute to broader efforts in optimizing urban mobility and reducing overall travel inefficiencies.

A significant proportion of respondents, approximately 75%, acknowledged the critical role of technology in enhancing the efficiency of their travel experiences. This finding underscores the necessity of implementing advanced computational techniques, such as graph algorithms, in navigation systems and public transportation applications. These algorithms, particularly Dijkstra's algorithm and the A* search algorithm, are integral to the optimization of route planning by analyzing various factors, including estimated travel time and prevailing road conditions. By leveraging these algorithms, navigation systems can provide travelers with more efficient and adaptive route recommendations, ultimately improving their overall travel experience.

Furthermore, a notable 37.5% of respondents indicated that the efficiency of their chosen routes had a substantial impact on their satisfaction with the journey. This highlights the essential function of graph-based computational models in modern transportation networks. The A* algorithm, for instance, is particularly effective in optimizing travel paths, as it integrates real-time variables such as current traffic conditions, road closures, and estimated arrival times. Unlike traditional shortest-path algorithms, A* incorporates heuristic evaluations that enable it to balance both speed and accuracy in determining the optimal route. Consequently, this algorithm enhances navigation systems by allowing for dynamic adjustments in response to real-time constraints, ensuring that users are provided with the most efficient travel routes available at any given moment.

The increasing reliance on digital technology in transportation further reinforces the significance of these algorithmic approaches. By integrating advanced route optimization techniques, navigation and public transportation systems can not only improve individual travel experiences but also contribute to broader urban mobility solutions. Efficient route recommendations, facilitated by graph algorithms, can lead to reduced congestion, lower travel costs, and enhanced sustainability in metropolitan transportation networks. Thus, the utilization of these algorithms plays a crucial role in shaping the future of intelligent and adaptive transportation systems (Prananta et al., 2024).

In computational problem-solving, algorithms are structured sets of steps designed to address specific challenges systematically. This study focuses on developing an algorithm to optimize the process of identifying bus routes within an urban transit network. The algorithm leverages a graph database to manage and analyze data related to bus rapid transit (BRT) routes. In accordance with the principles of graph databases, the transit network is represented using nodes and edges, where each node symbolizes a shelter or stop, and each edge represents a direct connection between two shelters. Both nodes and edges contain attributes that provide relevant contextual information, such as route identifiers, distances, and transfer points (Singh et al., 2024).

The primary objective of the algorithm is to facilitate efficient route searches, enabling users to determine the most suitable travel path from an origin node to a destination node. This search process can occur within a single transit corridor or across multiple corridors, depending on the connectivity of the network (Medlej et al., 2022). Several possible scenarios may arise during the route search process:

Unreachable Destination – In certain cases, the intended destination node may not be found, meaning there is no available corridor that connects the origin shelter to the target shelter. This scenario highlights gaps in the network or limitations in the existing transit infrastructure.

Direct Route Without Corridor Transfers – When a direct connection exists between the origin and destination nodes within the same corridor, passengers can travel seamlessly without requiring a transfer. For instance, if the starting shelter is A1 and the destination is A4, and both are located within the same transit corridor, the journey follows a single, uninterrupted route.

Route Requiring Corridor Transfers – In more complex cases, reaching the intended destination necessitates transferring between different corridors. This scenario occurs when the origin and destination shelters belong to separate transit routes, requiring passengers to switch corridors to complete their journey. For example, if the origin shelter is A1 and the destination shelter is B3, passengers must transition between corridors at an appropriate transfer point. Figure 3 provides a visual representation of this type of route search.

By implementing this algorithm, the study aims to enhance the efficiency of urban bus route planning, improving accessibility and reducing travel time for commuters.

The data model employed in this study represents three distinct transit corridors, designated as A, B, and C. However, the specific corridor information associated with the edges in the model is not explicitly displayed. Corridor A is directly linked to corridor B via shelter B2, while corridor B, in turn, connects to corridor C through the same shelter. This structural arrangement indicates that shelter B2 functions as a critical node within the transit network, serving as a junction with two branching connections: one extending within its respective corridor and the other facilitating inter-corridor connectivity. The model effectively captures the potential routes of the Bus Rapid Transit (BRT) system by incorporating these corridor linkages and transfer points. This representation provides a foundational framework for analyzing the network structure and optimizing route configurations. Moreover, the model is intended for use in the development of a graph database, where it will serve as a reference for structuring and storing transit data. By leveraging graph database techniques, the study aims to enhance the efficiency of route planning, passenger flow analysis, and network optimization. The inclusion of nodes, edges, and transfer points in this model contributes to a more comprehensive understanding of the spatial and operational dynamics of the BRT system. Furthermore, this modeling approach enables a more detailed examination of the interconnectivity between different corridors, potentially informing decision-making processes related to transit system design, scheduling, and capacity management. Through this structured representation, the study provides a systematic framework for evaluating transit networks, with implications for improving public transportation services and urban mobility planning.

Dijkstra's algorithm, a well-known method for determining the shortest path in a graph with positive weights, is widely applied in transportation networks to identify the most efficient route between two nodes. The algorithm operates on the fundamental principle of iteratively selecting the nearest unprocessed node and updating the minimum distance from the starting node to all other nodes in the graph. By following this process, it systematically explores the network, ensuring that the shortest path is identified at each step, ultimately providing the optimal route from the source to the destination (Dhanashri Korpad et al., 2024).

Empirical results from tests demonstrate several key advantages and limitations of Dijkstra's algorithm in transportation network optimization. First, regarding travel time efficiency, the algorithm consistently identifies the shortest route under normal traffic conditions, delivering superior travel times compared to conventional navigation systems that do not incorporate algorithmic optimization. This indicates that Dijkstra's approach is particularly valuable for enhancing the efficiency of route selection, minimizing unnecessary delays (Sohrabi & Lord, 2022).

Second, in terms of distance usage, the simulation outcomes indicate that the route generated by Dijkstra's algorithm consistently offers the shortest possible travel distance among all available options. This is a significant finding, as it demonstrates the algorithm's capacity to reduce energy consumption and fuel usage, making it a potentially crucial tool in the context of sustainable transportation. By minimizing the total travel distance, Dijkstra's algorithm not only optimizes the travel experience but also contributes to reducing the environmental impact of transportation (Ali et al., 2025).

However, despite these advantages, Dijkstra's algorithm does have notable limitations. A critical drawback is its failure to account for real-time dynamic factors such as traffic congestion, road closures, or accidents. As a result, while Dijkstra's algorithm may provide an optimal route under static conditions, its effectiveness diminishes in the presence of unpredictable traffic scenarios. The lack of adaptability to changing traffic conditions means that in heavy traffic, the route suggested by the algorithm may not always be the most optimal. Therefore, real-time data integration and dynamic updates would be necessary to enhance the algorithm's practical applicability in real-world, fluctuating environments.

The A* algorithm offers a distinct approach to pathfinding by integrating two key components: the cost from the starting point to the current node, denoted as g(n), and the estimated cost from the current node to the goal, represented by h(n), which is commonly referred to as the heuristic function. This combination of actual and estimated costs allows the A* algorithm to intelligently prioritize paths that are more likely to lead to the goal, thereby enhancing its efficiency in finding the shortest route. The results obtained from the application of A* in various transportation network scenarios highlight several advantages over traditional algorithms, such as Dijkstra's algorithm, which employs a purely exhaustive search approach (Bao, 2024).

One of the primary benefits of the A* algorithm is its superior travel time efficiency. In situations where a vast number of nodes must be evaluated, A* outperforms Dijkstra due to its use of heuristics that guide the search toward the most promising paths, thus reducing the time required to find an optimal route. This becomes particularly advantageous in complex network topologies, where limiting the search space can lead to significant reductions in computational effort and time. In contrast, Dijkstra's algorithm systematically examines every potential path, regardless of its relevance to the goal, leading to longer search times as the network grows in size and complexity.

Furthermore, A* demonstrates a notable advantage in route search speed, especially in large and intricate transportation networks. The use of a heuristic function enables A* to minimize the number of nodes it needs to explore by focusing only on those paths that are more likely to lead to the goal. This leads to a faster execution time, making A* particularly suited for dynamic environments where the transportation network is subject to frequent changes. On the other hand, Dijkstra's approach, which does not incorporate any form of heuristic, requires more time to process large-scale networks due to its exhaustive nature (Sun et al., 2024).

Another significant advantage of the A* algorithm is its dynamic adaptability. A* can be adjusted in real-time by modifying the heuristic function to account for external factors such as traffic density, weather conditions, or road closures. For example, if there is an unexpected traffic jam on a particular route, A* can quickly identify alternative routes that circumvent the congestion, providing a more flexible solution than Dijkstra. Dijkstra, by contrast, does not adapt to real-time conditions and focuses solely on the initial network configuration, which may lead to suboptimal route choices when external factors change.

To assess the practical implications of these algorithms, a comparison was conducted using historical urban transportation data, which included travel time and traffic density information. The performance of both the Dijkstra and A* algorithms was evaluated by comparing their results to the actual routes used by transportation users. The validation of the algorithms showed that under normal traffic conditions, both algorithms produced efficient routes that were consistent with the optimal routes identified in historical data.

However, under heavy traffic conditions, A* demonstrated its superiority by adjusting more effectively to dynamic changes in the network, while Dijkstra struggled to respond to such fluctuations in real-time (Afdhaluzzikri et al., 2024).

Simulations further reinforced these findings, showing that A* was capable of rapidly identifying alternative routes when faced with congestion, while Dijkstra continued to focus on finding the shortest path based on the initial data, without taking into account ongoing traffic conditions. This adaptability makes A* a more robust solution for real-time navigation, particularly in urban environments where traffic conditions can change rapidly.

In conclusion, the results of implementing both algorithms underscore the significant potential of graph algorithms, particularly A*, in enhancing the efficiency of modern transportation networks. The ability of A* to integrate real-time data, such as traffic and weather conditions, positions it as a critical component in the development of intelligent transportation systems (ITS). The application of these algorithms in urban transportation networks, especially in cities with high traffic density, can greatly improve route planning, reduce congestion, and optimize overall traffic flow, contributing to the advancement of smarter and more efficient transportation solutions.

CONCLUSION

This study demonstrates that both the Dijkstra and A* algorithms prove to be highly effective in identifying the shortest transportation routes within urban networks. The Dijkstra algorithm, characterized by its robustness in stable conditions, is particularly well-suited for small-scale networks where the primary focus is minimizing travel distance. In contrast, the A* algorithm is more appropriate for large-scale and dynamic transportation networks that necessitate real-time adjustments due to changing traffic conditions. The results from validation and simulation further substantiate the superior responsiveness of the A* algorithm, particularly in situations where congestion arises, as it efficiently provides alternative routes to circumvent traffic bottlenecks. This feature of A* makes it a more optimal solution for addressing transportation challenges in high-traffic environments. Therefore, the findings of this study lend support to the growing application of graph-based algorithms, especially the A* algorithm, as integral components of intelligent transportation systems (ITS). These systems, which leverage advanced algorithms, can significantly enhance the efficiency of urban travel by adapting to varying traffic conditions and helping users reach their destinations in a timely manner. For future research, it is recommended to extend the application of these algorithms within ITS frameworks that incorporate real-time traffic data, investigate additional algorithmic solutions for more complex and larger-scale networks, and enhance datasets by integrating external variables to improve the precision and scalability of transportation optimization strategies in urban settings.

REFERENCES

Afdhaluzzikri, M., Santriawan, L. D., Sapni, E., Nugroho, M. S., & Romdhini, M. U. (2024). Application of Dijkstra Algorithm in Determining Transportation Costs for Tourist Attractions in Lombok Island Based on the Shortest Path. *Jurnal Pariwisata Nusantara (JUWITA)*, *3*(2), 67–73. https://doi.org/10.20414/juwita.v3i2.11017

Ali, N., Hussain, A., & Bokhari, S. W. A. (2025). Optimizing maritime routes. *Croatian Operational Research Review*, *16*(1), 73–83. https://doi.org/10.17535/crorr.2025.0007

Bao, Y. (2024). Proposed Outlook based on Different Obstacle Avoidance and Pathfinding Algorithms. *Applied and Computational Engineering*, *97*(1), 83–88. https://doi.org/10.54254/2755-2721/97/20241268

Dhanashri Korpad, Nisha Satpute, Nayana Joshi, Snehal Kulkarni, Komal Walgude, & Neha Dhadiwal. (2024). Numerical Data Processing by The Implementation of Trees and Graphs. *International Research Journal on Advanced Engineering and Management (IRJAEM)*, *2*(11), 3256–3260. https://doi.org/10.47392/IRJAEM.2024.0479

Gera, B., Hermaniuk, Y., & Matviiv, V. (2023). Organization of passenger rail transportation on the section with the combined track Nyzhankovychi- Starzhava. *Transport Technologies*, *2023*(1), 29–37. https://doi.org/10.23939/tt2023.01.029

Jung, I. (2024). Week 7: Writing the Qualitative Methods Section. In *Pathways to International Publication in the Social Sciences* (pp. 135–145). Springer Nature Singapore. https://doi.org/10.1007/978-981-96-0801-0_13

Kotov, T. (2025). Global logistics networks as an imperative for the sustainable development of the world economy. *Herald of Economics*, *4*, 66–76. https://doi.org/10.35774/visnyk2024.04.066

Likaj, R., Bajrami, X., Hoxha, G., & Shala, E. (2024). *The Application of the Dijkstra Algorithm in the Finding of the Optimal Solution for the Connected Road Network to Center Prishtina* (pp. 86–97). https://doi.org/10.1007/978-3-031-48933-4_9

Medlej, A., Dedu, E., Dhoutaut, D., & Beydoun, K. (2022). *Efficient Retransmission Algorithm for Ensuring Packet Delivery to Sleeping Destination Node* (pp. 219–230). https://doi.org/10.1007/978-3-030-99587-4_19

Prananta, A. W., Kuswandoro, W. E., Afifuddin, M., Rahma, P. D., & Mulyaningsih, H. (2024). Digital Transformation in Industrial Technology and Its Social Impact on Online Public Transportation. *Join: Journal of Social Science*, *1*(3). https://doi.org/10.59613/eh78zj02

R. Vinodhini. (2025). Applications of Discrete Mathematics in Computer Science: Algorithms, Graph Theory, and Beyond. *Communications on Applied Nonlinear Analysis*, *32*(7s), 210–220. https://doi.org/10.52783/cana.v32.3378

Rane, N., Paramesha, M., Choudhary, S., & Rane, J. (2024). Business Intelligence and Artificial Intelligence for Sustainable Development: Integrating Internet of Things, Machine Learning, and Big Data Analytics for Enhanced Sustainability. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4833996

Singh, R., Wangmo, D., Kaushik, K., & Chaudhary, A. (2024). An Algorithmic Approach Using Fuzzy Soft Sets in Decision- Making for Patient-Specific Diagnosis. *2024 International Conference on Emerging Innovations and Advanced Computing (INNOCOMP)*, 200–206. https://doi.org/10.1109/INNOCOMP63224.2024.00040

Sohrabi, S., & Lord, D. (2022). Navigating to safety: Necessity, requirements, and barriers to considering safety in route finding. *Transportation Research Part C: Emerging Technologies*, *137*, 103542. https://doi.org/10.1016/j.trc.2021.103542

Sun, Q., Pang, J., Wang, X., Zhao, Z., & Li, J. (2024). A Clustered Routing Algorithm Based on Forwarding Mechanism Optimization. *IEEE Sensors Journal*, *24*(22), 38071–38081. https://doi.org/10.1109/JSEN.2024.3467055

Yang, C., Mao, J., Qian, X., & Wu, E. Q. (2024). Robustness Optimization of Air Transportation Network With Total Route Cost Constraint. *IEEE Transactions on Automation Science and Engineering*, 1–15. https://doi.org/10.1109/TASE.2024.3391763

Yoo, Y.-D., & Moon, J.-H. (2025). Study on A-Star Algorithm-Based 3D Path Optimization Method Considering Density of Obstacles. *Aerospace*, *12*(2), 85. https://doi.org/10.3390/aerospace12020085

Zhou, J., Shen, J., Fu, C., Weibel, R., & Zhou, Z. (2025). Quantifying indoor navigation map information considering the dynamic map elements for scale adaptation. *International Journal of Applied Earth Observation and Geoinformation*, *136*, 104323. https://doi.org/10.1016/j.jag.2024.104323