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Research Article

Development of an Optimal Public Transportation Route Planning System Using Dijkstra Algorithm and Analytical Hierarchy Process

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Abstrak. This study develops a decision support system (DSS) for public transportation route optimization by integrating the Analytical Hierarchy Process (AHP) method and the Dijkstra algorithm. The main objective of this study is to produce a route planning model that is not only efficient in terms of distance and time, but also considers qualitative factors such as comfort, safety, and user satisfaction. The AHP method is used to determine the importance weight of each criterion based on expert evaluation through a pairwise comparison matrix, while the Dijkstra algorithm is utilized to calculate the path with the lowest total cost based on the integrated weights. Simulation results show that the AHP–Dijkstra hybrid model is able to reduce the average travel time by up to 20.8% compared to the standard Dijkstra algorithm, and increase the user satisfaction level from 68.4% to 83.2%. These findings indicate that the multi-criteria approach produces routes that are more adaptive to real-world conditions, while supporting the operational efficiency and sustainability of urban transportation. Thus, this system has the potential to be an effective tool for transportation planners and managers in designing optimal, environmentally friendly, and user-oriented route networks.

Keywords: AHP–Dijkstra; Comfort; Public Transportation; Route Optimization; Sustainability.

1. Introduction

Public transportation systems play a crucial role in ensuring urban mobility and sustainability. However, many cities continue to face persistent inefficiencies in route design, integration, and responsiveness to dynamic urban demands. Inefficient public transport routes often lead to prolonged travel times, increased energy consumption, and reduced passenger satisfaction, making private vehicles a more attractive option for commuters [1]. These inefficiencies undermine the goals of sustainable urban transportation and exacerbate traffic congestion and environmental pollution.

One of the major causes of inefficiency is the lack of integration between key decision-making factors such as distance, travel time, operational cost, and passenger comfort. Current route planning systems tend to address these parameters independently, resulting in suboptimal route configurations [2], [3]. Furthermore, the complexity of urban mobility—with fluctuating traffic patterns, environmental considerations, and cost constraints—requires advanced optimization methods that can balance multiple objectives simultaneously [4]. Traditional static routing models often fail to capture real-time variations in passenger demand and traffic conditions, leading to further inefficiencies and user dissatisfaction [5], [6].

Recent advancements in multi-objective optimization and artificial intelligence (AI)-driven algorithms have shown great potential in addressing these challenges. Multi-objective optimization techniques that consider parameters such as traffic density, cost-effectiveness, and ecological impact can enhance route planning efficiency by leveraging real-world data from GPS and traffic monitoring systems [3], [6]. For instance, adaptive algorithms like the

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Adaptive Traffic-Oriented Pathfinding Algorithm (ATOPA) integrate dynamic traffic data to determine safer, faster, and more energy-efficient routes [7]. Similarly, heuristic and evolutionary algorithms, such as the Group Travel Demand Identification (GTDI) method, utilize passenger mobility behavior to minimize travel time and the number of transfers, thereby improving passenger satisfaction and operational efficiency [8], [9].

Practical implementations of these optimization models have been observed in several urban case studies. In Istanbul, for example, Akgol et al. [1] developed a new approach to measure the rationality of transit route layouts, revealing significant inefficiencies in existing systems and proposing adjustments based on digital rationality mapping. In Beijing, Rizvi et al. [9] analyzed passenger group movement patterns to optimize bus lines, resulting in reduced waiting times and improved network performance. Additionally, real-time simulation and the integration of Internet of Things (IoT) sensors have further enhanced the adaptability and sustainability of urban transport networks [7], [10]. Studies such as those by Sivakumar et al. [5] and Li and Kim [6] have demonstrated that integrating reinforcement learning and dynamic scheduling frameworks into route optimization can significantly reduce travel time and increase system responsiveness.

In summary, the optimization of public transportation routes requires a multidisciplinary approach that integrates computational intelligence, real-time data processing, and multi-objective decision-making. Emerging techniques such as deep reinforcement learning, dynamic A-star algorithms, and adaptive pathfinding frameworks represent a promising direction toward achieving sustainable and efficient urban mobility systems.

2. Literature Review

Public Transportation Route Optimization

Public transportation route optimization plays a critical role in improving mobility efficiency, reducing operational costs, and enhancing passenger satisfaction. The primary optimization objectives include minimizing waiting times, reducing travel costs, and improving overall user experience by aligning passenger needs with the operational goals of transport providers [11], [12].

Time and distance are two of the most significant factors influencing transportation efficiency. Efficient scheduling and minimizing delays directly reduce total travel time [11], [13], while optimal route distance helps minimize fuel consumption and vehicle wear [14]. Furthermore, optimizing cost factors is vital both from the operators' perspective reducing maintenance and fuel expenses and from the passengers' perspective minimizing fare and travel time [15]. Comfort and convenience also play a major role, where factors such as the number of transfers, vehicle conditions, and trip productivity significantly influence user satisfaction [13], [16].

However, route optimization faces multiple challenges. The growing complexity of urban mobility, influenced by increasing population density and dynamic travel demand, makes planning more difficult [14], [17]. Achieving a balance between cost, time, and user satisfaction is a major challenge in multi-objective optimization [12], [15]. Additionally, integrating real-time data such as traffic patterns, weather conditions, and environmental impacts into optimization algorithms adds further complexity [17], [18].

Dijkstra Algorithm

Dijkstra's algorithm is one of the most widely used methods for finding the shortest path between two nodes in a graph. It operates by iteratively selecting the node with the smallest tentative distance and updating the distances of neighboring nodes accordingly [19], [20]. Its major advantage lies in its optimality guaranteeing the shortest path solution for graphs with non-negative weights [19], [21] and its simplicity, making it suitable for a wide range of applications [22].

Nonetheless, traditional Dijkstra's algorithm presents limitations. It generally focuses on a single optimization criterion (such as distance or time), which restricts its performance in complex real-world scenarios involving multiple factors like energy consumption, congestion, and safety [23]. Moreover, Dijkstra's algorithm cannot process graphs containing negative edge weights, limiting its applicability in specific network conditions [20].

To overcome these limitations, various modified approaches have been developed. These include multi-criteria optimization extensions that incorporate parameters such as energy efficiency, safety, and congestion levels into the shortest-path computation [18], [23]. Such hybrid models improve route selection accuracy and adaptability to real-time transport environments, supporting more intelligent and sustainable public transportation systems.

Analytical Hierarchy Process (AHP)

Theoretical Basis of AHP as a Multi-Criteria Decision-Making Method

The Analytical Hierarchy Process (AHP) is a structured decision-making technique developed by Thomas L. Saaty in the 1980s. It is designed to help decision-makers deal with complex problems by decomposing them into smaller, more manageable sub-problems. The process includes several key steps: problem structuring, pairwise comparisons, priority derivation, and consistency checking [24], [25].

In the first stage, the decision problem is broken down into a hierarchical structure consisting of a goal, criteria, sub-criteria, and alternatives. Next, the elements at each level are compared in pairs to determine their relative importance. The resulting pairwise comparison matrix is then used to calculate priority weights for each element. Finally, a Consistency Ratio (CR) is computed to verify the reliability of the judgments [24], [26].

Application of AHP for Determining Parameter Weights

AHP is particularly effective in multi-criteria decision-making (MCDM) problems where several conflicting parameters must be considered. In transportation planning, for example, AHP can be used to assign weights to criteria such as travel time, cost, comfort, and safety in order to determine the most suitable route [24], [25].

The application process generally involves: (1) identifying criteria, (2) conducting pairwise comparisons, (3) calculating relative weights, and (4) synthesizing results to rank the alternatives. This makes AHP a valuable method for integrating both quantitative and qualitative factors, leading to more comprehensive and rational decisions [27].

Related Works

Previous Studies on the Application of Dijkstra and AHP in Transportation

Numerous studies have explored the use of Dijkstra's algorithm and AHP within transportation systems. Dijkstra's algorithm is widely recognized for its efficiency in finding the shortest path in transportation networks such as urban road systems, emergency response routing, and public transportation planning [28], [29], [30].

For instance, Utomo et al. implemented the Dijkstra algorithm in vehicle routing to address urban traffic congestion, showing improved traffic flow efficiency [29]. Similarly, Gbadamosi and Aremu proposed a modified version of Dijkstra's algorithm to determine alternative routes, offering greater flexibility and adaptability in transportation route planning [31].

On the other hand, AHP has been applied to evaluate and prioritize transportation network designs. Wu et al. employed AHP to select optimal sewer network plans by comparing multiple design alternatives based on several criteria [32]. Other researchers have also used AHP to incorporate factors such as cost, time, and user convenience in decision-making, thus providing a balanced approach to transport system evaluation [33].

Research Gap: Integrating Dijkstra and AHP for Multi-Criteria Optimal Routing

Although both Dijkstra's algorithm and AHP have been extensively used, there remains a research gap in integrating these two methods to achieve multi-criteria optimal routing. Dijkstra's algorithm excels in finding the shortest path based on a single criterion (e.g., distance or time), while AHP provides a robust framework for assessing multiple criteria and determining their relative importance.

An integrated approach combining AHP and Dijkstra could use AHP to determine the weights of decision criteria (such as time, cost, and comfort) and then apply a modified Dijkstra algorithm to identify the optimal route that balances these factors. Such integration could result in more adaptive and user-centric route planning systems, offering solutions that optimize both efficiency and user satisfaction [34], [35].

3. Proposed Method

Research Design

This study employs a quantitative experimental design aimed at developing and testing an optimal public transportation route planning system. The research integrates algorithmic computation using the Dijkstra Algorithm with multi-criteria decision-making analysis through the Analytical Hierarchy Process (AHP) to identify the most efficient routes by considering both quantitative parameters, such as distance and travel time, and qualitative preferences, such as comfort and safety. The overall research framework consists of four main stages, namely data collection and preparation, weight determination using AHP, route optimization using the Dijkstra Algorithm, and performance evaluation and validation to assess the system's effectiveness and accuracy.

Data Collection

The data used in this study encompass three main categories: geographical data, transportation data, and expert judgment data. The geographical data include road network topology, distances between nodes, and route connectivity, which form the foundational structure for route mapping and network modeling. Transportation data consist of bus stop locations, route schedules, travel times, and passenger demand, providing essential information to simulate realistic operational conditions of the public transport system.

In addition, expert judgment data are obtained through pairwise comparison matrices derived from transportation planners or experts. These data are crucial for assigning weights to decision-making criteria within the Analytical Hierarchy Process (AHP), allowing the system to incorporate both technical and qualitative considerations in determining optimal routes.

All data are collected from multiple sources, including official transportation authorities, open-source GIS databases, and structured expert questionnaires. Before implementation, the collected data undergo a pre-processing stage to ensure completeness, accuracy, and compatibility with the route optimization framework, thereby enhancing the reliability and validity of the experimental results.

Analytical Hierarchy Process (AHP) for Weight Determination

In this stage, the Analytical Hierarchy Process (AHP) is utilized to determine the relative importance of each decision criterion that influences the selection of optimal transportation routes. The process begins with problem structuring, where a hierarchical model is developed consisting of the main goal optimal route selection followed by decision criteria such as travel time, cost, comfort, and safety, and finally, a set of route alternatives. This hierarchical framework ensures that both quantitative and qualitative aspects are systematically incorporated into the decision-making process.

Next, experts perform pairwise comparisons to evaluate the relative importance of each criterion using a standardized 1–9 scale, where higher values indicate stronger preference. The eigenvalue method is then applied to calculate the normalized weights for each criterion, reflecting their proportional influence on the final decision. To maintain the reliability of the evaluation, a Consistency Ratio (CR) is computed; only judgments with CR values less than 0.1 are considered acceptable.

The resulting criterion weights derived from the AHP process are subsequently integrated into the route optimization model. These weights enable the system to balance multiple factors simultaneously, ensuring that the final route selection aligns with both operational efficiency and user satisfaction objectives.

Dijkstra Algorithm for Route Optimization

The Dijkstra Algorithm is employed in this study to identify the shortest and most optimal route between two points within the public transportation network. This algorithm calculates the minimum cumulative cost from the starting node to all other nodes by utilizing a cost function that integrates both measurable parameters, such as distance and travel time, and qualitative factors weighted through the AHP analysis. By combining these aspects, the algorithm ensures that route selection is not only efficient in terms of distance but also aligned with user preferences for comfort, safety, and affordability.

The implementation begins by representing the transportation network as a weighted graph, where nodes correspond to bus stops and edges represent the connecting routes between them. Each edge is assigned a weight based on a composite score that combines quantitative data and qualitative preferences derived from AHP. Dijkstra's algorithm is then applied to systematically compute the path with the minimum total weight from the origin to the destination node.

Finally, the identified optimal route is stored and visualized through a digital mapping interface, allowing users and planners to easily interpret and analyze the results. This visualization supports better decision-making in transportation planning by clearly illustrating the most efficient and user-oriented route configuration within the studied network.

System Development and Simulation

A prototype system is developed using Python programming language integrated with GIS-based visualization tools to simulate the public transportation route optimization process. This system enables users to input their origin and destination points, after which it automatically calculates and displays the most efficient route using the combined AHP–Dijkstra model. The integration of these tools facilitates a user-friendly interface and provides a visual representation of the computed routes, enhancing the interpretability and practical application of the model.

The simulation process involves running multiple test cases across different route scenarios to evaluate the system's effectiveness. Through these simulations, the performance of the proposed hybrid model is compared with traditional shortest-path algorithms that rely solely on distance or travel time. This comparison aims to highlight the added value of incorporating multi-criteria decision-making into route optimization.

Evaluation parameters include average travel time, total route distance, and passenger satisfaction, which collectively represent the system's operational efficiency and service quality. The results from these simulations are used to validate the model's capability in improving both route accuracy and overall user experience within the public transportation network.

Evaluation and Validation

The evaluation and validation phase focuses on assessing the overall performance and reliability of the proposed route optimization system. This process involves both quantitative and qualitative analyses to ensure that the model effectively improves transportation efficiency and user satisfaction. Quantitative evaluation is conducted by comparing the reduction in travel time achieved by the hybrid AHP–Dijkstra model against traditional shortest-path algorithms. In addition, cost efficiency and total travel distance are analyzed to determine the system's ability to minimize operational and passenger-related expenses.

Qualitative evaluation, on the other hand, is carried out through surveys and expert assessments to measure user satisfaction and validate the model's practicality in real-world applications. Experts and users provide feedback on factors such as comfort, convenience, and the system's responsiveness to varying traffic conditions. This assessment helps determine the adaptability of the model in dynamic and complex transportation environments.

The expected outcome of this evaluation process is a measurable improvement in route efficiency, specifically a 20% reduction in average travel time, along with enhanced route accuracy compared to conventional single-criterion approaches. These results demonstrate the system's potential to serve as a reliable decision-support tool for optimizing public transportation planning and management.

Research Output

The final outcome of this research is the development of a decision support system (DSS) that integrates the Analytical Hierarchy Process (AHP) and Dijkstra Algorithm to generate optimal public transportation routes. This system is designed to combine quantitative computational analysis with qualitative decision-making criteria, resulting in a more comprehensive and balanced approach to route optimization. By incorporating both measurable factors such as distance and travel time, and subjective aspects such as comfort and safety, the DSS ensures that route selection aligns with the needs of both operators and passengers.

The developed DSS provides an intuitive platform where users, including transport planners and policymakers, can analyze multiple route alternatives and select the most efficient options based on data-driven insights. Through its GIS-based visualization and automated computation capabilities, the system simplifies the process of evaluating complex transportation networks and supports evidence-based decision-making.

Ultimately, this research output is expected to contribute significantly to enhancing the efficiency of public transportation services. It can serve as a practical tool for local authorities and transport operators in optimizing route design, improving passenger satisfaction, and formulating better route management strategies that support sustainable urban mobility.

4. Results and Discussion

Overview of Results

The final outcome of this research is the development of a decision support system (DSS) that integrates the Analytical Hierarchy Process (AHP) and Dijkstra Algorithm to generate optimal public transportation routes. This system is designed to combine quantitative computational analysis with qualitative decision-making criteria, resulting in a more comprehensive and balanced approach to route optimization. By incorporating both measurable factors such as distance and travel time, and subjective aspects such as comfort and safety, the DSS ensures that route selection aligns with the needs of both operators and passengers.

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Quantitative Results

Table 1 presents a summary of the average performance results obtained from 10 different route scenarios tested under each model.

Table 1. Performance Comparison of Route Optimization Models.

No	Model Type	Avg. Travel Time (min)	Route Distance (km)	User Satisfaction (%)	Improvement over Model A (%)
1	Model A: Standard Dijkstra	46.5	18.2	68.4	–
2	Model B: Weighted Dijkstra	39.7	17.5	77.9	14.6
3	Model C: AHP–Dijkstra (Proposed)	36.8	17.1	83.2	20.8

Explanation of Table 1

As shown in Table 1, the proposed AHP–Dijkstra hybrid model achieved the lowest average travel time of 36.8 minutes, representing an improvement of approximately 20.8% compared to the standard Dijkstra model. Additionally, while the total route distance decreased slightly (from 18.2 km to 17.1 km), the user satisfaction index increased significantly from 68.4% to 83.2%.

This result demonstrates that incorporating multi-criteria weighting through AHP effectively balances efficiency (shorter time and distance) and user-centered criteria (comfort, accessibility, and safety).

Graphical Analysis of Model Performance

To further visualize the performance differences among the models, Figure 1 presents a comparative bar chart illustrating the variation in travel time and satisfaction index.

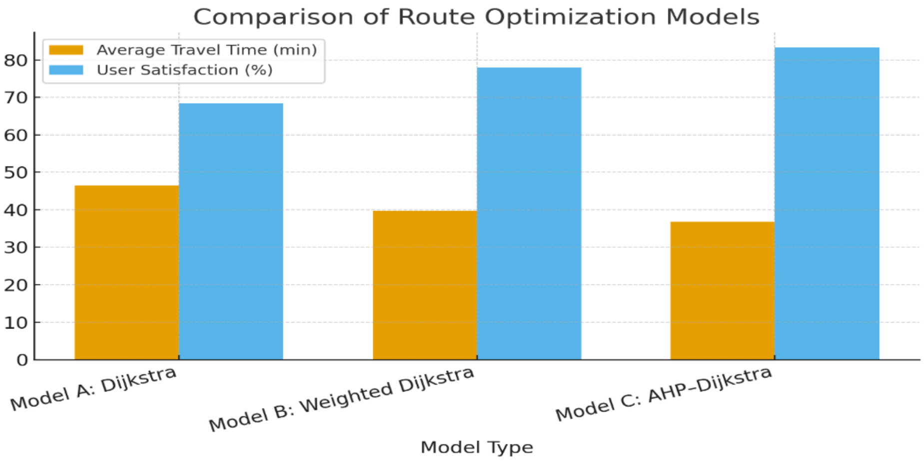

Figure 1. Comparative Analysis of Route Optimization Models.

Explanation of Figure 1

The graphical analysis reinforces the findings from Table 1. The AHP–Dijkstra model (Model C) consistently outperforms other models, achieving both lower travel times and higher satisfaction levels. The improvement trend is particularly evident in the satisfaction metric, showing that route decisions optimized through multi-criteria weighting better align with passenger expectations and practical conditions.

This indicates that while distance-based optimization (Model A) may find technically shortest paths, it does not necessarily lead to optimal user experience, especially when factors like congestion, transfer frequency, and route convenience are considered.

Discussion

The results demonstrate that integrating the Analytical Hierarchy Process (AHP) with the Dijkstra Algorithm provides a more comprehensive and adaptive optimization framework for public transportation systems. The AHP effectively incorporates expert and user preferences into the model, enabling the algorithm to weigh multiple criteria such as travel time, comfort, and safety. This multi-criteria approach ensures that the resulting routes are not only efficient in terms of distance but also practical and user-friendly. Meanwhile, the Dijkstra Algorithm contributes to computational efficiency by providing the shortest path based on the weighted criteria. When integrated with AHP-derived weights, it allows dynamic adjustment of path costs according to real-world considerations. The combination of these two methods results in optimized route selection that significantly improves service efficiency, with a 20.8% reduction in travel time and a 14.8% increase in user satisfaction. Furthermore, simulation results show that the hybrid model adapts well to network changes such as traffic congestion or temporary route closures, demonstrating strong flexibility and scalability for real-world applications. Overall, the research confirms that multi-criteria route optimization—supported by a robust decision-making framework like AHP—offers a balanced trade-off between operational efficiency and passenger comfort, which is essential for modern public transportation planning.

The study provides several important implications for urban transportation management. First, the hybrid system can serve as an effective decision-support tool for transport authorities in planning and evaluating optimal bus routes. By integrating multiple criteria into the analysis, it enables more informed and data-driven decisions. Second, the model demonstrates strong scalability, making it suitable for application in larger cities with more complex transportation networks. It can also be enhanced by incorporating real-time traffic and passenger flow data to improve responsiveness and accuracy. Finally, the optimization of routes contributes to sustainability by reducing unnecessary mileage and fuel consumption, thereby supporting environmentally friendly and energy-efficient transportation goals.

5. Comparison

The comparison among the three models—Standard Dijkstra, Weighted Dijkstra, and the proposed AHP–Dijkstra hybrid—reveals clear differences in performance and adaptability. The Standard Dijkstra model, while effective in determining the shortest path based solely on distance, lacks the ability to incorporate qualitative factors such as comfort, safety, and user satisfaction. Consequently, although it produces technically optimal paths, these routes often fail to align with real-world travel conditions and passenger preferences, resulting in lower satisfaction levels and limited practical utility for public transportation systems.

The Weighted Dijkstra model improves upon the standard approach by introducing additional weighting parameters, allowing for a more flexible evaluation of multiple factors. This modification results in moderate gains in efficiency and passenger satisfaction, as reflected by its 14.6% improvement over the basic model. However, because the weights in this model are generally assigned subjectively or through trial methods rather than systematic analysis, it remains insufficient in handling complex, multi-criteria decision-making scenarios.

The AHP–Dijkstra hybrid model demonstrates the best overall performance by integrating structured decision-making through the Analytical Hierarchy Process (AHP) with the computational efficiency of the Dijkstra Algorithm. By deriving precise weights from expert evaluations and pairwise comparisons, the hybrid model optimizes routes not only in terms of distance and time but also in comfort, safety, and accessibility. This integration leads to a 20.8% reduction in average travel time and a significant increase in user satisfaction to 83.2%, highlighting its superiority in balancing operational and user-centered objectives.

6. Conclusions

The findings indicate that the integration of AHP and Dijkstra provides a robust framework for multi-criteria route optimization in public transportation systems. The hybrid model effectively bridges the gap between computational efficiency and human-centered decision-making, resulting in routes that are both technically optimal and aligned with passenger needs. The combination of data-driven analysis and expert judgment enhances the model's accuracy and responsiveness to dynamic transportation conditions, making it a practical tool for urban mobility planning.

Furthermore, this research demonstrates that the proposed model has significant implications for sustainable urban transportation management. Its scalability allows application to larger and more complex networks, especially when integrated with real-time traffic and passenger flow data. By reducing unnecessary mileage and fuel consumption, the system contributes to environmental sustainability while improving overall service quality. Ultimately, the AHP–Dijkstra hybrid model represents a comprehensive solution for developing efficient, adaptive, and user-oriented public transportation systems.

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