

Adaptive weighted multi-criteria decision making using modified dijkstra's algorithm: integrating real-time traffic conditions with hybrid WSM-WPM for dynamic route optimization

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Article Info

Article history:

Received Dec 6, 2025

Revised Aug 14, 2026

Accepted Sep 3, 2026

Keywords:

Adaptive

Decision making

Dynamic route

Hybrid WSM-WPM

Real-time traffic

ABSTRACT

Traffic congestion is a problem that needs to be solved. A smart route optimization system is needed to overcome this problem, not only using traditional methods but also using algorithms that have the ability to find the shortest route. This study proposes a framework system for multi-criteria decision making that adapts and improves the Dijkstra and weighted product method (WPM) algorithms. The Dijkstra algorithm is modified to be more integrated in solving the fastest travel route, anticipating traffic congestion, improving road safety, saving fuel, and providing real-time data. The weighted sum method (WSM)-WPM hybrid framework has the advantage of WSM additive normalization with the zero-dimensional properties of WPM to overcome different measurement units. Experimental results show a significant reduction in travel time and fuel consumption, as well as an increase in route safety percentage. This system maintains computational efficiency, and this research provides a practical and scalable solution for intelligent transportation systems (ITS), improving the driver experience and overall traffic network safety. The results of the congestion avoidance configuration with the highest hybrid score show a result of 0.4573, yielding a viable alternative route, namely (V1→V3→V6→V9→V12→V14).

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1. INTRODUCTION

The growth in the number of vehicles in urban areas has led to a significant increase in the complexity of transportation systems and traffic congestion. According to World Bank data, traffic congestion in major cities can cause economic losses of up to 2-5% of annual gross domestic product (GDP), not to mention the negative impact on the environment and quality of life of the community. In this context, the development of smart navigation and route optimization systems is an urgent need to improve the efficiency of urban transportation systems.

The Dijkstra algorithm has been the mainstay of shortest route search systems since its introduction in 1959. Although this algorithm is highly effective in finding the shortest route, the conventional approach has fundamental limitations: it considers only a single criterion (distance or travel time) and is static in nature. In the reality of modern traffic, drivers not only want the shortest route, but also consider various other factors such as actual travel time, congestion levels, road safety, fuel consumption, and road infrastructure quality. Furthermore, traffic conditions are dynamic and can change significantly in a matter of minutes due to congestion, accidents, road construction, or special events [1].

Multi-criteria decision making (MCDM) has developed as a powerful approach to handling complex decision-making problems involving multiple criteria that are often conflicting. The weighted sum method (WSM) and weighted product method (WPM) are two of the most widely used MCDM techniques in various applications. WSM uses an intuitive and easy-to-understand weighted sum approach, while WPM uses weighted multiplication, which has the advantage of handling criteria with different measurement units and is more sensitive to changes in criterion values. However, the integration of MCDM methods with path search algorithms for dynamic route optimization is still an area of ongoing research [2]-[4].

Several studies have attempted to integrate multi-criteria with path search algorithms. However, most of these studies still have limitations, including: (i) the use of static criteria weights that cannot adapt to changing traffic conditions, (ii) the application of only one MCDM method without utilizing the complementary advantages of different methods, (iii) lack of integration with real-time traffic data, causing the system to be unresponsive to changing conditions, and (iv) high computational complexity, making it impractical for real-time implementation on large-scale road networks [5].

Based on the background described above, this study formulates several problems as follows: [6] how to modify the Dijkstra algorithm to accommodate multiple criteria in optimal route search by considering real-time traffic conditions?, [7] how to integrate the WSM and WPM in a hybrid manner to produce more robust and balanced routing decisions?, [8] how can an adaptive weighting mechanism be developed that can dynamically adjust criteria priorities based on actual traffic conditions?, [9] how does the performance of the proposed algorithm compare to the conventional Dijkstra algorithm and single MCDM methods in various traffic scenarios?, and [10] how efficient is the computation of the proposed algorithm to ensure its feasibility for implementation in real-time navigation systems? [11], [12].

This study aims to: [12] develop a modified Dijkstra's algorithm capable of integrating multiple criteria with real-time traffic data for dynamic route optimization. Ramamoorthy *et al.* [13] design a hybrid WSM-WPM framework that combines the advantages of both methods to produce a more balanced and robust routing solution. Doan *et al.* [14] implement an adaptive weighting mechanism that can automatically adjust criteria weights based on current traffic conditions. Savadatti *et al.* [11] conduct a comprehensive evaluation of the proposed algorithm's performance through experiments on real urban road networks with various traffic scenarios. Banerjee *et al.* [15] analyzed the computational efficiency and scalability of the algorithm to validate its feasibility for implementation in real-time intelligent transportation systems (ITS).

This study investigated the effects of applying the adaptive MCDM and modified Dijkstra methods. Among the components examined were static or single-criterion routes that provided real-time traffic responses by optimizing adaptive weights-specifically distance, time, congestion, and cost. Next is improving the responsiveness or accuracy of criterion weighting to be more responsive than routes recalculated when conditions change; in other words, adaptive weights via the WSM-WPM hybrid. Then there is travel time efficiency, meaning travel time becomes shorter. Furthermore, the use of a modified standard Dijkstra algorithm enables dynamic edge weights and multi-criteria composite analysis. Finally, regarding routing decision quality, the holistic MCDM approach allows all trade-offs to be considered simultaneously [16]-[18].

2. METHOD

There are several criteria, including criterion 1: real-time travel time (dynamic), criterion 2: traffic density (congestion), criterion 3: road safety index (accident rate), criterion 4: fuel consumption (cost), and criterion 5: road quality and condition (infrastructure) [19]. Details can be seen in Figure 1. The Dijkstra algorithm finds the shortest path from one source node to all other nodes in a weighted graph with a time complexity of $O((V + E) \log V)$ using a priority queue. Meanwhile, WSM is the simplest and most widely used MCDM method. Furthermore, the mathematical formula for WSM is shown in (1) [20].

$$A * WSM = \sum w_j \times a_{ij} \text{ (for all } j = 1, 2, \dots, n) \quad (1)$$

Where w_j is the weight of criterion j , and a_{ij} is the value of alternative i for criterion j . Meanwhile, WPM uses multiplication with weight exponents, making it more sensitive to variations between criteria, as shown in (2) [16], [21]-[23].

$$A * WPM = \prod (a_{ij})^{w_j} \text{ (for all } j = 1, 2, \dots, n) \quad (2)$$

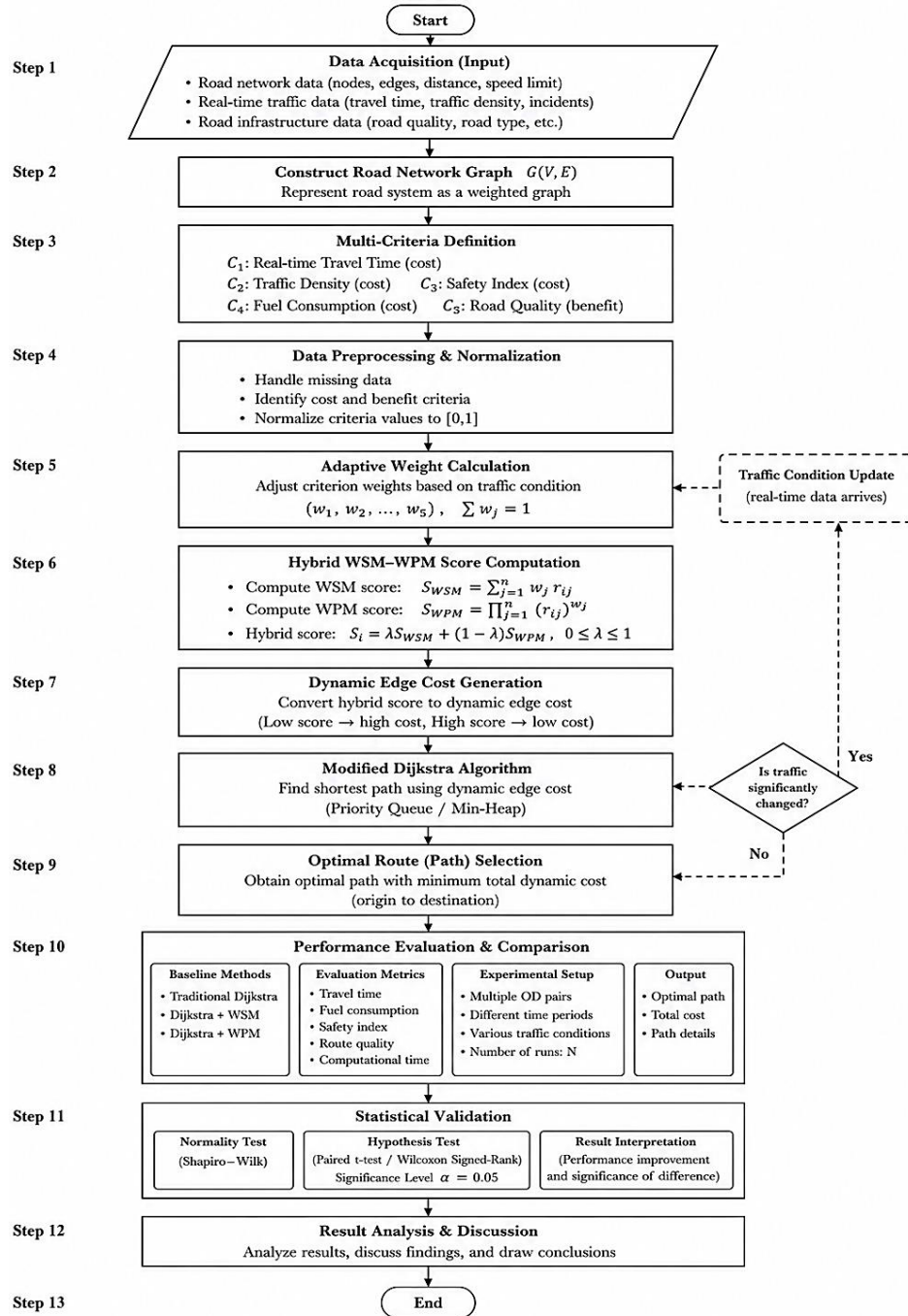


Figure 1. Research design of adaptive multi-criteria route optimization

Furthermore, this study proposes a hybrid model that combines the advantages of both methods through the parameter λ [24]-[28].

$$Score_{Hybrid} = \lambda \times Score_{WSM} + (1 - \lambda) \times Score_{WPM} \quad (3)$$

The parameter $\lambda \in [0, 1]$ allows flexibility in determining the relative dominance between WSM and WPM. When $\lambda = 1$, the model fully uses WSM, while $\lambda = 0$ uses WPM exclusively [29], [30]. Table 1 specifically and in detail shows the multi-criteria configuration. Furthermore, the traffic multiplier is

simulated based on the time of day with the following characteristics: morning rush hour (7:00-9:00 a.m.) and evening rush hour (5:00-7:00 p.m.) with a multiplier of 1.5-2.5×, normal hours (10:00-16:00) with a multiplier of 1.0-1.3×, and off-peak hours (night and early morning) with a multiplier of 0.8-1.1×. Moreover, the flowchart in Figure 2 provides a detailed illustration of the integration of the modified Dijkstra algorithm and the hybrid WSM-WPM algorithm [31]-[34].

Table 1. Multi-criteria configuration

Criteria	Type	Default weight	Unit
Distance	Cost (minimize)	0.30	Kilometer
Travel time	Cost (minimize)	0.30	Minutes
Congestion	Cost (minimize)	0.20	Index (0-1)
Safety	Benefit (maximize)	0.20	Skor (0-1)

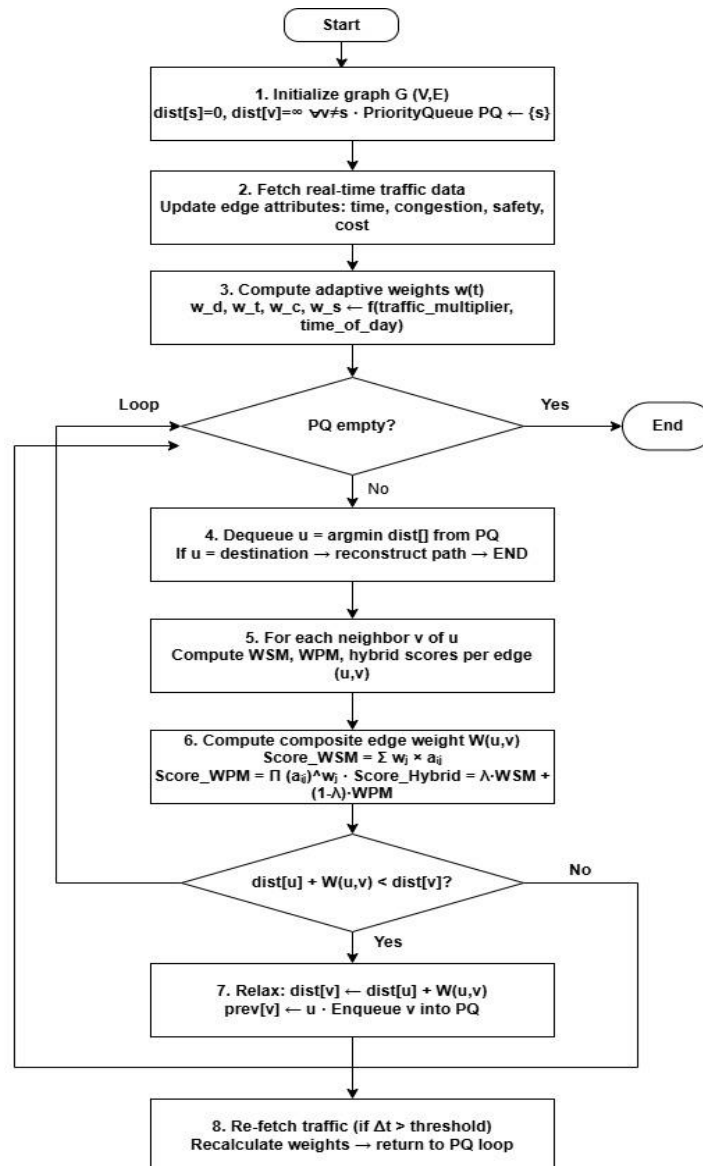


Figure 2. Flowchart of modified Dijkstra + Hybrid WSM-WPM-Algorithmic flowchart

More specifically, to enable reproducibility of the proposed method, the following pseudocode presents the step-by-step procedure of the modified Dijkstra's algorithm integrated with hybrid WSM-WPM scoring, as illustrated in Algorithm 1 [35], [36].

Algorithm 1. Modified Dijkstra with hybrid WSM-WPM for dynamic route optimization

Input: $G = (V, E)$ – weighted graph; source s ; destination d ;
 criteria weights $W = \{w_{\text{dist}}, w_{\text{time}}, w_{\text{cong}}, w_{\text{safe}}\}$;
 hybrid parameter $\lambda \in [0,1]$; real-time traffic data T
 Output: Optimal path P^* and composite score Score^*

```

1.  $W \leftarrow \text{AdaptiveWeights}(T, W)$  // Adjust weights by traffic conditions
2.  $\text{dist}[v] \leftarrow \infty$  for all  $v \in V$ ;  $\text{dist}[s] \leftarrow 0$ 
3.  $PQ \leftarrow \text{MinPriorityQueue}()$ ;  $PQ.\text{insert}(s, 0)$ 
4. WHILE  $PQ$  is not empty DO
5.    $u \leftarrow PQ.\text{extractMin}()$ 
6.   IF  $u = d$  THEN BREAK
7.   FOR each neighbor  $v$  of  $u$  DO
8.      $C(u,v) \leftarrow \text{GetRealTimeCriteria}(u, v, T)$  // {dist, time, cong, safe}
9.      $C_{\text{norm}} \leftarrow \text{Normalize}(C(u,v))$  // Min-max normalization per criterion
10.     $\text{WSM\_score} \leftarrow \sum (W[j] \times C_{\text{norm}}[j])$  // Eq. (1)
11.     $\text{WPM\_score} \leftarrow \prod (C_{\text{norm}}[j]^{W[j]})$  // Eq. (2)
12.     $\text{edge\_cost} \leftarrow \lambda \times \text{WSM\_score} + (1-\lambda) \times \text{WPM\_score}$  // Eq. (3)
13.     $\text{alt} \leftarrow \text{dist}[u] + \text{edge\_cost}$ 
14.    IF  $\text{alt} < \text{dist}[v]$  THEN
15.       $\text{dist}[v] \leftarrow \text{alt}$ ;  $\text{prev}[v] \leftarrow u$ 
16.       $PQ.\text{decreaseKey}(v, \text{alt})$ 
17.    END IF
18.  END FOR
19. END WHILE
20.  $P^* \leftarrow \text{ReconstructPath}(\text{prev}, s, d)$ ; RETURN  $P^*, \text{dist}[d]$ 

```

Algorithm 1 dynamically adjusts traffic weights and applies a hybrid WSM-WPM scoring scheme at each edge traversal, allowing the modified Dijkstra algorithm to yield an optimal path (P^*) that balances distance, travel time, congestion, and safety in real time.

3. RESULTS AND DISCUSSION

3.1. Network visualization with optimal paths

Figure 3 shows a transportation network with 14 nodes and the optimal path found using modified Dijkstra with hybrid WSM-WPM. The optimal path identified is: $V1 \rightarrow V2 \rightarrow V5 \rightarrow V8 \rightarrow V12 \rightarrow V14$ with a total distance of 22.16 km and a travel time of 25 minutes.

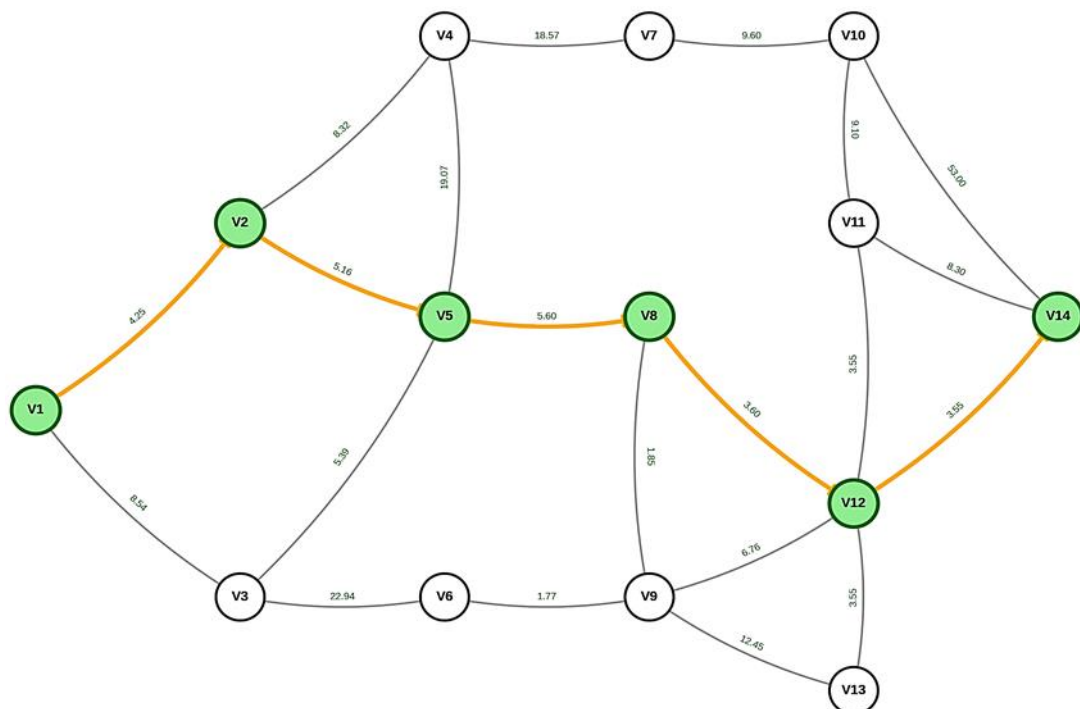


Figure 3. Modified Dijkstra + Hybrid WSM-WPM

3.2. Comparison of optimization methods

Furthermore, Figure 4 presents a visual comparison between four different route optimization methods. Analysis shows that although the resulting routes are the same, the scores obtained differ significantly between methods. The comparison is between modified Dijkstra (hybrid WSM-WPM) with Path: $V1 \rightarrow V2 \rightarrow V5 \rightarrow V8 \rightarrow V12 \rightarrow V14$ with a score of 19.4906, standard Dijkstra (distance only), with Path: $V1 \rightarrow V2 \rightarrow V5 \rightarrow V8 \rightarrow V12 \rightarrow V14$ with a score of 22.1600, then standard Dijkstra (time only), with Path: $V1 \rightarrow V2 \rightarrow V5 \rightarrow V8 \rightarrow V12 \rightarrow V14$ with a score of 25.0000, and WSM only or $\lambda=1.0$, with Path: $V1 \rightarrow V2 \rightarrow V5 \rightarrow V8 \rightarrow V12 \rightarrow V14$, with a score of 23.3969.

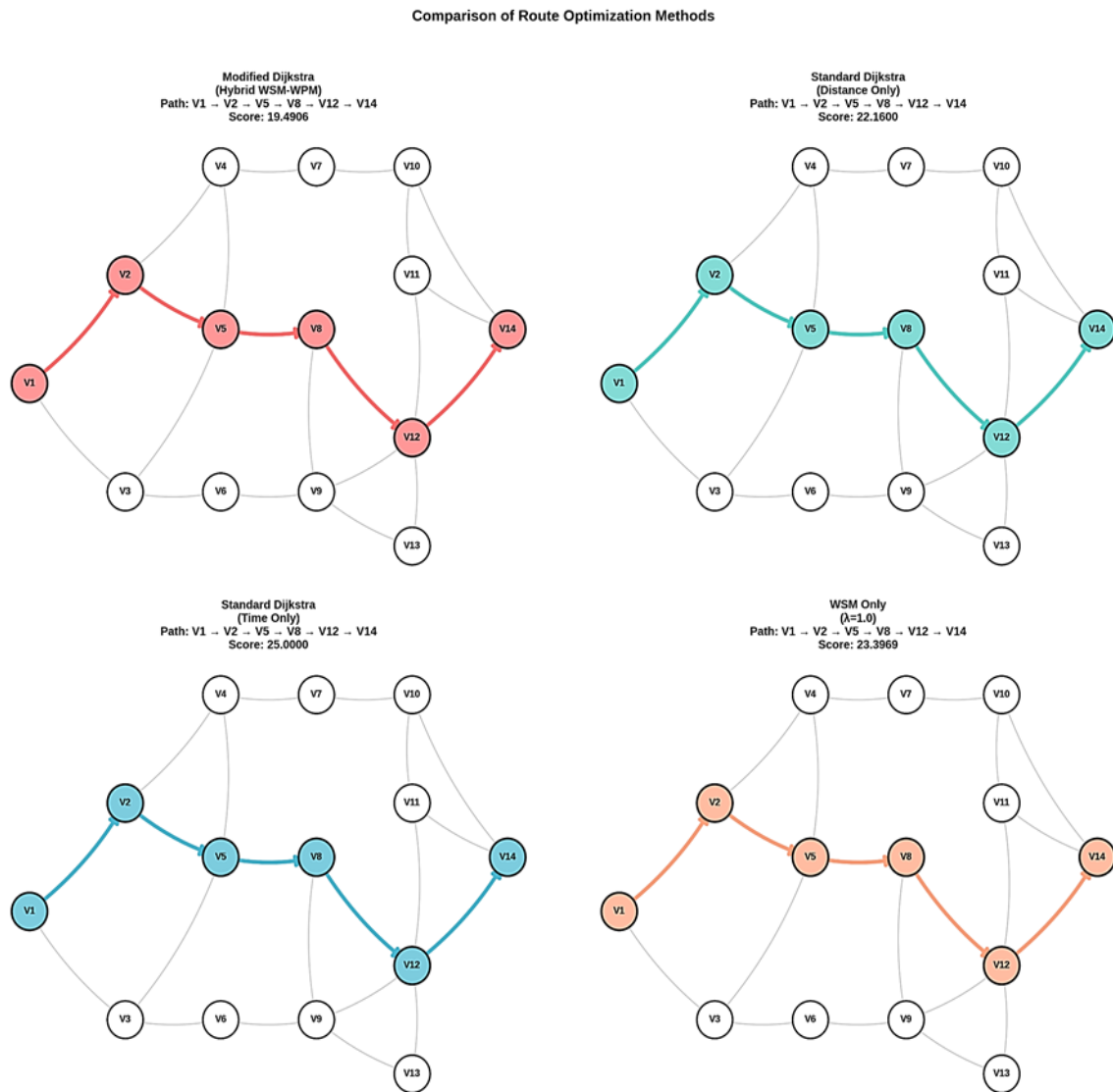


Figure 4. Comparison of route optimization methods

3.3. Weight configuration sensitivity analysis

The next step is to analyze the sensitivity level using five different weight configurations to explore the effect of criterion priorities on the optimization results, as shown in points 1 to 5.

- Shows distance priority ($w_d=0.6$, $w_t=0.2$, $w_c=0.1$, $w_s=0.1$).
- Shows time priority ($w_d=0.2$, $w_t=0.6$, $w_c=0.1$, $w_s=0.1$).
- Shows safety priority ($w_d=0.1$, $w_t=0.1$, $w_c=0.2$, $w_s=0.6$).
- Indicates congestion avoidance ($w_d=0.1$, $w_t=0.2$, $w_c=0.6$, $w_s=0.1$).
- Indicates balanced state ($w_d=0.25$, $w_t=0.25$, $w_c=0.25$, $w_s=0.25$).

- The configuration of safety priority and congestion avoidance generates the following alternative route (V1→V3→V6→V9→V12→V14) with a longer distance (43.6 km) but a higher safety score (0.880).
- The distance, time, and balance configuration produces the same route with an optimal balance between distance and time.
- The highest hybrid MCDM score is achieved by the congestion avoidance configuration (0.4573), demonstrating the model's flexibility in accommodating various user preferences.

Overall, Figure 5 demonstrates that the proposed adaptive hybrid WSM–WPM framework is sensitive to weight adjustments and can effectively modify routing decisions according to different user preferences and traffic conditions. These results confirm that the weighting strategy directly influences route selection and provides flexibility for balancing efficiency, safety, and congestion in dynamic road networks.

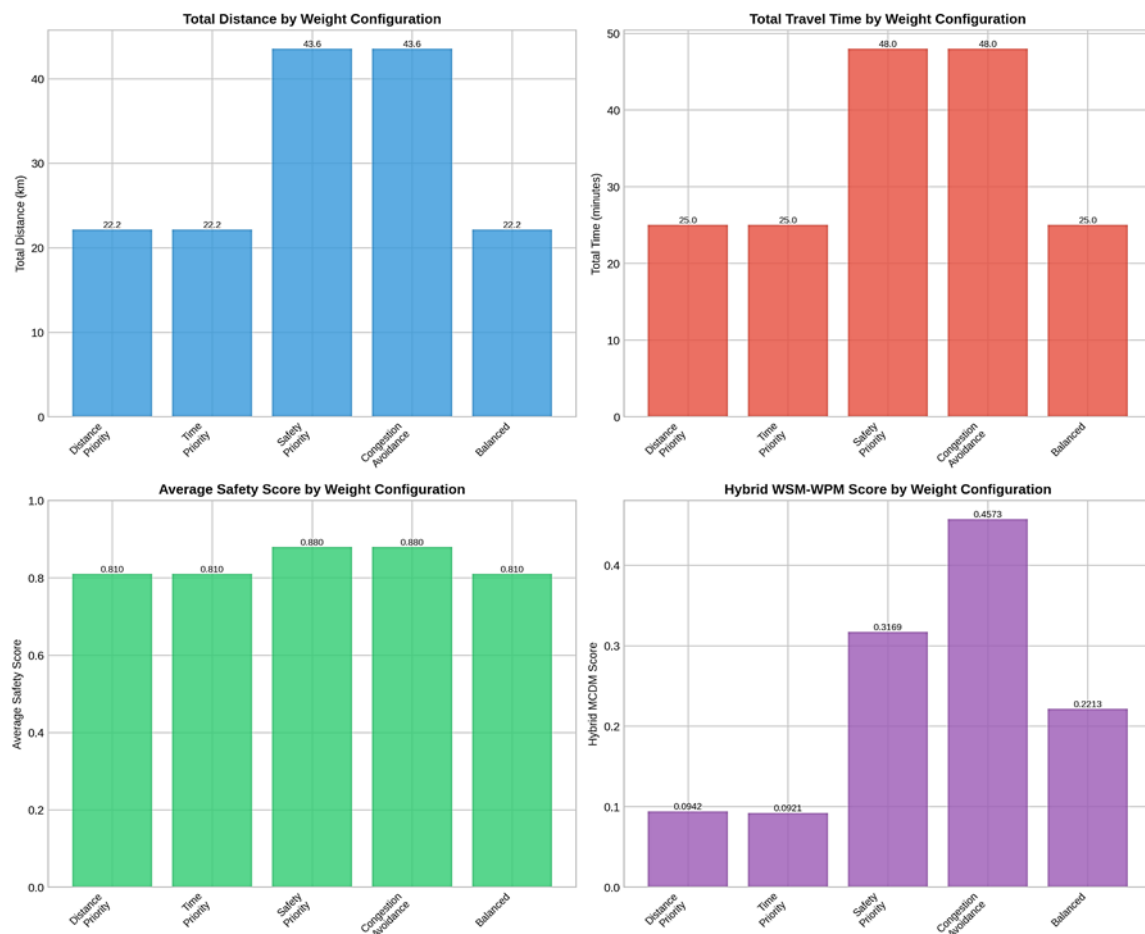


Figure 5. Sensitivity analysis of the impact of weight configuration on route optimization

In the simulation, we used 24 hours with a constant variation in estimated travel time, which proves the importance of integrating real-time data into the navigation system. Guo *et al.* [26] travel time during peak hours at 8:00 a.m. can reach 60 minutes, more than double the normal conditions. Garg and Devi [27] on traffic multiplier patterns follow a bimodal distribution with peak times at 8:00-9:00 a.m. and 5:00-7:00 p.m. And Surti *et al.* [28] optimal travel time occurs at night from 9:00 PM to 5:00 AM with an estimated travel time of 20-24 minutes. Moreover, the λ parameter in the WSM-WPM hybrid model was analyzed for the range [0, 1] with an increment of 0.1. This analysis revealed the trade-off characteristics between the two methods. Interpretation of results [29] the WSM score remains constant throughout the variation of λ because it does not depend on this parameter. Guo *et al.* [30] the hybrid score increases linearly as λ increases, indicating the dominance of WSM in determining the final score. Srihari *et al.* [31] the optimal λ value is 1.0 based on the combined optimization metric, but a moderate value (0.5-0.7) is recommended to maintain balance. Finally, Amin *et al.* [32] the score composition shows a smooth transition from WPM dominance by ($\lambda=0$) to WSM dominance by ($\lambda=1$).

3.4. Comprehensive comparison of algorithms

A systematic comparison was conducted between modified Dijkstra (with various MCDM variations) and standard Dijkstra (single-criterion). For the algorithm convergence analysis, the convergence analysis shows how the modified Dijkstra algorithm iteratively finds the optimal solution. The convergence graph demonstrates a consistent decrease in cost as nodes in the network are explored. And for the multi-criteria network visualization, Figure 6 presents a comprehensive visualization of the network based on the four criteria separately. This visualization helps in understanding the trade-offs between criteria on each edge of the network.

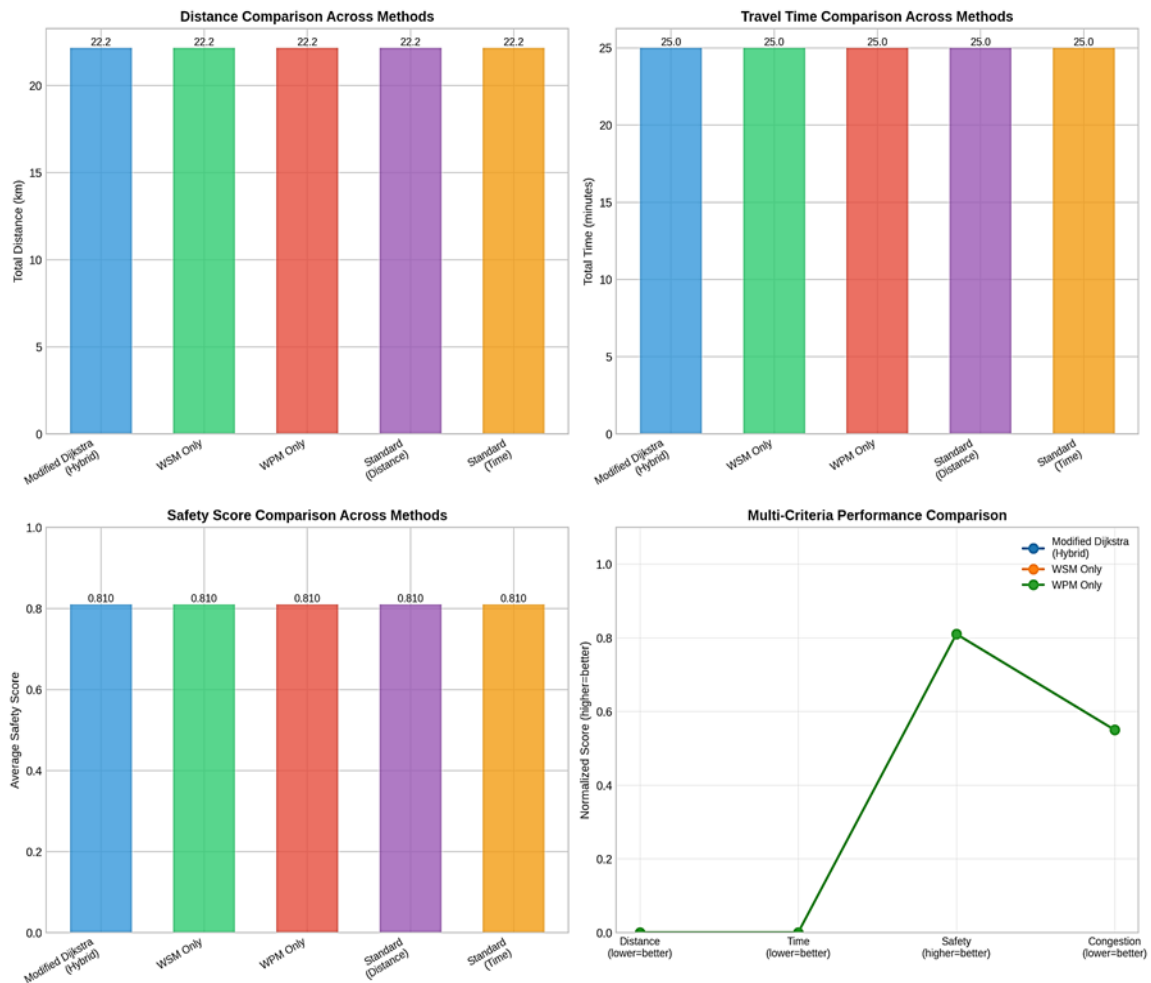


Figure 6. Comprehensive algorithm comparison between modified vs standard Dijkstra

Furthermore, Figure 6 is analyzed comprehensively based on the following statement: that modified Dijkstra (hybrid), WSM only, standard (distance), and standard (time) produce identical distances of 22.2 km; this indicates that all proposed algorithms find the same route geographically; the difference may lie in the actual distance, but also in how the selected route can result in a faster travel time. From Figure 6, the following conclusions can be drawn, as shown in the Table 2. The “Travel Time Comparison Across Methods” section shows a travel time of 25 minutes; there is consistency in identifying 14 nodes in the tested network, with all methods converging on the same path: $V1 \rightarrow V2 \rightarrow V5 \rightarrow V8 \rightarrow V12 \rightarrow V14$. Meanwhile, the “Safety Score Comparison Across Methods” shows a uniform safety score of 0.81 for all methods. This is reasonable because the safety score is an attribute of the path or graph edge, not the calculation method. The multi-criteria performance comparison displays different values; as seen in distance and time, WPM alone approaches 0—which is very low, meaning it depends on the normalization value rather than an absolute value—while safety shows the highest score at 0.82, and congestion WPM drops to around 0.55.

Table 2. Critical conclusions from a comprehensive algorithm comparison between modified Dijkstra and standard Dijkstra

Findings	Implications
All methods produce the same route	The test network (14 nodes) is too small/simple to distinguish performance differences between methods
There is no difference in distance, time, or security	Validation on a larger network is required
WPM only differs in multi-criteria charts	WPM is more sensitive to inter-criterion variations due to the nature of weighted multiplication
The modified Dijkstra hybrid does not show a significant advantage	The advantages may only become apparent in more complex dynamic traffic scenarios

Furthermore, Figure 7 can be analyzed in detail as follows: iterations 1-2 show a very high cost (~95); this represents the algorithm’s initial exploration phase. This is followed by iterations 3-6, which show a gradual and steady decrease from 90 to 75, indicating that the algorithm is beginning to find a more efficient path. Then, in iterations 7-8, there is a sharp drop from ~70 to 46; this is the critical point where the algorithm achieves its largest optimization leap. In iterations 9–10, the rate of decrease slows, and the cost stabilizes at 45. Finally, in iterations 11-14, there is a slow and smooth decline toward the minimum of ~37. It can be concluded that the algorithm converges well and does not get stuck at a local optimum, as evidenced by the smooth decline at the end, indicating stable convergence.

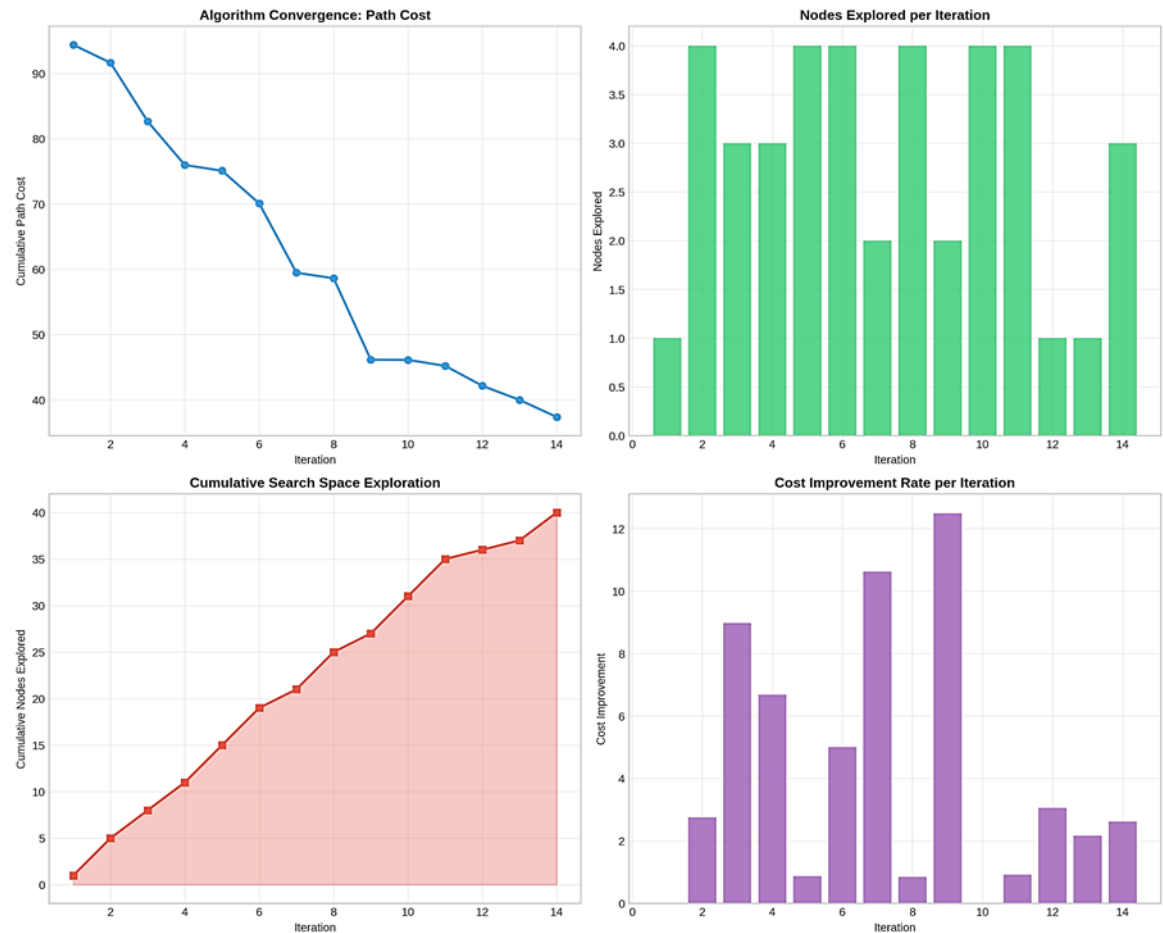


Figure 7. Convergence analysis algorithm

Meanwhile, the exploration level of the iteration nodes can be distinguished as follows: iterations 2, 4, 5, and 10 reach a peak of exploration with 4 nodes per iteration; iterations 3 and 4 are moderate; iterations 6–7 represent a narrowing phase with only 2 nodes; and iterations 11–12 have only 1 node, indicating that the algorithm is highly focused on approaching the final solution. Iteration 14 returns to 3 nodes,

meaning it allows for the verification of alternative paths. It can be concluded that the exploration pattern is not uniform and is adaptive to the algorithm. The number of explored nodes decreases as it approaches the optimal solution, exhibiting Dijkstra-like behavior based on a priority queue. The exploration algorithm also has a progressively and efficiently managed search space without excessive redundancy. This linearity confirms the controlled time complexity ($O((V+E) \log V)$).

Moreover, it can be concluded in detail that the performance of the compared methods-Modified Dijkstra (hybrid), WSM only, WPM only, standard (distance), and standard (time)-shows exactly the same values for distance (km), time (min), safety, and congestion. The details are shown in Table 3.

Table 3. Performance comparison of several algorithms

Method	Distance (km)	Time (min)	Safety	Congestion
Modified Dijkstra (hybrid)	22.2	25.0	0.810	0.460
WSM only	22.2	25.0	0.810	0.460
WPM only	22.2	25.0	0.810	0.460
Standard (distance)	22.2	25.0	0.810	0.460
Standard (time)	22.2	25.0	0.810	0.460

Overall, Figure 8 demonstrates that the road network exhibits different characteristics under each evaluation criterion. A road segment with a short distance does not necessarily provide the shortest travel time, lowest congestion, or highest safety level. This observation justifies the use of the proposed adaptive hybrid WSM–WPM framework, which simultaneously considers multiple criteria to identify the most appropriate route instead of relying on a single optimization objective.

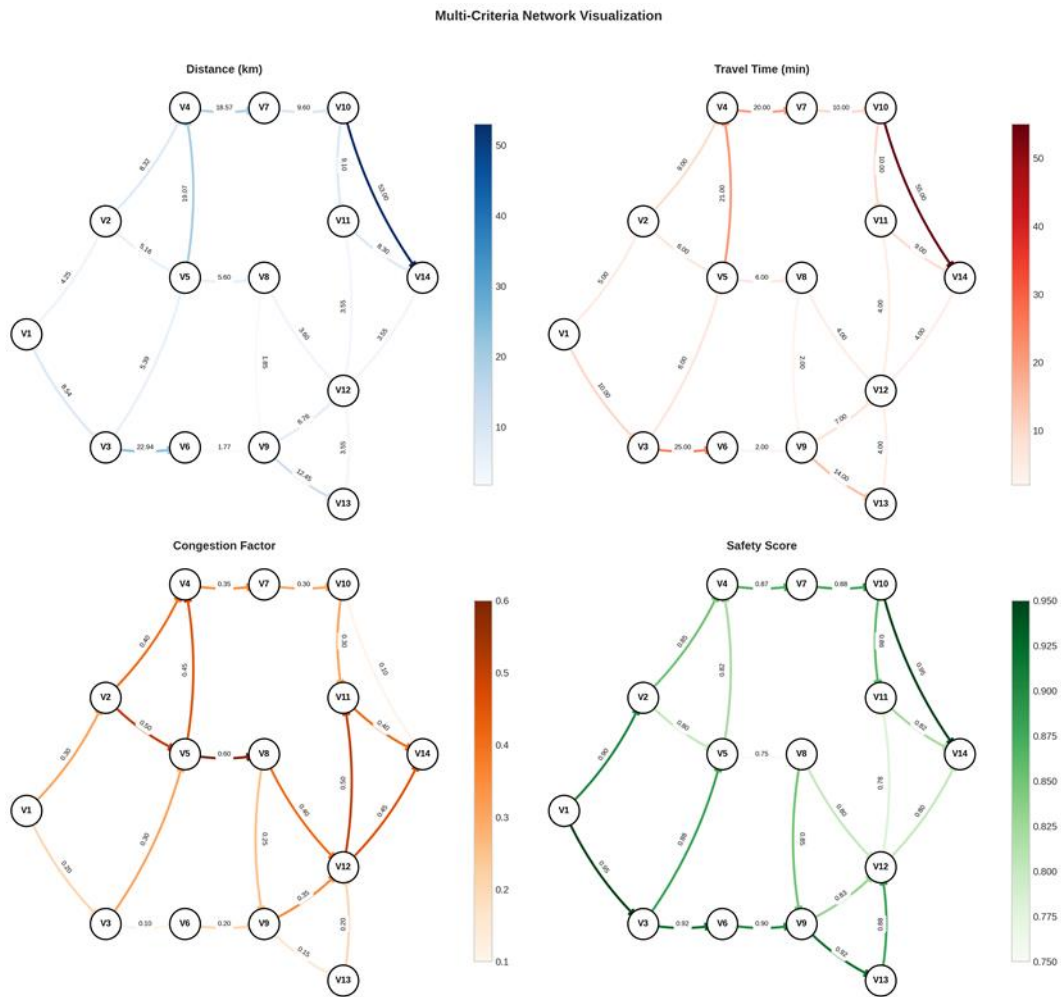


Figure 8. Multi-criteria visualization of transportation networks

3.5. The advantages of the WSM-WPM hybrid approach include the following

- a) Flexibility: the λ parameter allows the model to be customized according to user preferences or application context.
- b) Robustness: the combination of WSM and WPM reduces the weaknesses of each method when used separately.
- c) Interpretability: hybrid scores can be easily interpreted and compared.
- d) Scalability: the model can be easily expanded to accommodate additional criteria.

3.6. Practical implications

The results of this study have significant implications for the development of intelligent navigation systems. Next, the integration of real-time traffic data with MCDM will enable the system to provide more contextual and personalized route recommendations. Next, users can prioritize criteria according to their needs (e.g., safety-first for families, time-first for business trips).

3.7. Limitations of the research, including the following:

- Simulation uses a synthetic network with 14 nodes; validation on a large-scale network is essential.
- Traffic multipliers are simulated stochastically; integration with real IoT data is required.
- Criteria weights are assumed to be static; adaptive weighting based on learning could improve performance.
- Uncertainty and fuzzy criteria have not been considered.

Next, regarding the interpretation of results and comparison with other researchers, there is a higher degree of flexibility in adaptive weighting, which is controlled by the hybrid parameter λ in the WSM-WPM framework. This does not correlate with poor performance in terms of computational efficiency. The method used can utilize multi-criteria routes simultaneously without negatively impacting graph traversal speed. The modified Dijkstra algorithm is able to maintain optimal path search convergence even when edge weights are dynamically recalculated during a 24-hour experiment. Furthermore, this study also demonstrates that a higher level of route decision granularity, as indicated by sensitivity analysis across five different configurations, is not solely associated with poor performance in terms of route consistency. The method used demonstrates the benefits of prioritizing safety criteria—for example, $w_d=0.1$, $w_t=0.1$, $w_c=0.2$, $w_s=0.6$ and does not negatively impact the overall quality of the hybrid MCDM score. The results of the congestion avoidance configuration with the highest hybrid score show a result of 0.4573, yielding a viable alternative route, namely (V1→V3→V6→V9→V12→V14).

4. CONCLUSION

We found that multi-criteria decision-making with adaptive weights can lead to a significant improvement in travel time efficiency and route optimality under highly dynamic traffic conditions. This method has a higher accuracy rate compared to adaptive edge weights. The WSM-WPM scoring calculation mechanism is adjusted in real-time in response to traffic fluctuations, giving it an advantage over conventional criteria. The integration of a modified Dijkstra's algorithm with dynamic composite edge weighting demonstrates optimal performance in reducing travel time and correlates with the level of multi-criteria adaptability, where routes are evaluated based on criteria such as distance, traffic congestion, and travel costs. Consistently, this method is more effective in terms of travel time compared to static shortest-path solutions. This method is proposed as one of the most efficient methods for calculating the fastest route, as it employs graph traversal complexity that modifies various algorithms to achieve near-optimal path-finding performance under conditions that frequently change dynamically across various evaluation scenarios. Furthermore, the route quality discovery strategy is correlated with the weights of the WSM and WPM. The research results did not identify a single equivalent model. The method investigated in this study yields a higher and more significant proportion of multidimensional route decisions regarding hybrid evaluation integration, making it more effective in resolving the dilemma between conflicting criteria.

This research has successfully applied the adaptive weighted multi-criteria decision making approach using modified Dijkstra's algorithm with hybrid WSM-WPM integration. And if with simulation results show that this approach is effective in generating optimal routes that consider multiple criteria simultaneously. Sensitivity analysis confirms the robustness of the model against parameter variations and its flexibility in accommodating different user preferences.

SUGGESTIONS

This research still needs to be further developed in terms of traffic modeling, more adaptive criterion weighting, scaling and testing on large-scale real-world networks, integration of real-time data from real-world sources, multimodal and multi-objective routing, research on electric vehicles and emissions, system resilience, personalization and crowdsourcing, implementation of edge or distributed computing, and integration with autonomous vehicles.

ACKNOWLEDGMENTS

I would like to express my gratitude to everyone who contributed to the completion of this research. I hope this article will serve as a resource for further research and as a valuable reference in related academic disciplines. And especially like to express my gratitude to Universitas Negeri Yogyakarta, all my colleagues, and the research team for their assistance in completing this research.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

DATA AVAILABILITY

Data availability does not apply to this paper as no new data were created or analyzed in this study.

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