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MULTI-CRITERIA MODEL FOR THE FORMATION OF AN URBAN BUS ROUTE NETWORK UNDER UNCERTAINTY

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ABSTRACT

Urban bus network design becomes especially challenging when passenger demand, running times, and operating conditions vary over time. This paper proposes a decision framework for comparing route alternatives under such uncertainty without collapsing the problem into a single performance indicator. The framework combines system analysis, dynamic programming, and multi-criteria optimization. Candidate routes are evaluated with respect to travel time, waiting time, headway, number of transfers, transport cost, service quality, and reliability. Operational inputs can be refreshed from GPS/GNSS records, passenger-flow observations, dispatching logs, and electronic fare-collection data, allowing the evaluation to respond to changing conditions. The procedure first generates feasible alternatives, then removes dominated solutions and retains a Pareto-efficient set for final managerial selection. The resulting structure links passenger demand, operating constraints, and service-quality considerations within a transparent workflow. For Nukus, the model offers a basis for periodically reassessing route choices as demand and operating conditions change. Rather than producing a single universal optimum, the approach identifies a defensible set of efficient alternatives from which planners can choose according to available fleet resources and policy priorities.

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Keywords: *urban bus network; multi-criteria optimization; uncertainty; dynamic programming; Pareto efficiency; passenger demand; GPS/GNSS monitoring; public transport planning.*

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Introduction

Designing an urban bus network is a balancing problem rather than a shortest-path exercise. A route that performs well in terms of distance may be less attractive when waiting time, transfers, operating cost, reliability, or service coverage are considered simultaneously. For this reason, route planning should reflect both passenger experience and operator constraints instead of relying on a single indicator.

The planning task is also inherently dynamic. Demand is usually concentrated during morning and evening peaks, road congestion alters running times, and travel intensity may differ between weekdays and weekends. If these variations are represented by fixed average values, the resulting network may fail to match actual operating conditions. A more useful model therefore needs to accept updated demand and operational data and reassess route alternatives when the underlying conditions change.

Research conducted in Uzbekistan has highlighted several components relevant to this problem. Integrated evaluation has been used to describe the state of urban public transport infrastructure (Matrasulov & Yo‘ldoshev, 2025), while intelligent transport research has emphasized the role of real-time information, sensor-based observation, and data integration in management processes (Mirzabekov &

Kurbonova, 2025). Work on bus regularity has focused on schedule deviation and headway stability (Jurayev & Ikromov, 2025), and passenger-flow forecasting has been linked to the need to align service supply with demand (Abdullayev, 2025). Taken together, these studies show that route planning benefits from combining infrastructure, operational, and demand-related evidence.

The international literature provides a broader methodological foundation. Reviews of multi-criteria decision-making (MCDM) in transport show that such methods are well suited to problems in which objectives conflict and no single measure can represent overall performance (Keshavarz-Ghorabaee et al., 2022). Fuzzy AHP has been proposed for cases in which travel demand and user preferences cannot be expressed with complete certainty (Alkharabsheh et al., 2022). Integrated timetable and vehicle-scheduling studies further demonstrate the value of Pareto-efficient solutions when several objectives are optimized simultaneously (Liu et al., 2023). The increasing availability of heterogeneous transport data also creates opportunities to update planning decisions using multiple digital sources (Urbano et al., 2025), while fuzzy decision frameworks offer additional support when data are incomplete or imprecise (Kilic & Demirel, 2025).

Bus-network research also shows that demand varies across both space and time and that passengers, operators, and public authorities do not necessarily pursue identical objectives (Ibarra-Rojas et al., 2015). Earlier network-optimization studies similarly stressed the need to consider passenger costs and transfers when evaluating route structures (Mandl, 1980). Where explicit criterion weights are required, the Analytic Hierarchy Process remains a widely used tool for structuring relative priorities (Saaty, 1980).

Against this background, the purpose of this study is to formulate a route-evaluation model that can compare feasible bus-network alternatives under uncertain operating conditions and identify a set of Pareto-efficient options rather than forcing a single predetermined optimum.

Materials and Methods. A staged analytical procedure was constructed using system analysis, object-oriented representation of transport elements, decision theory, dynamic programming, and multi-criteria optimization. The procedure follows the analytical logic developed in the underlying dissertation but is organized here as a reproducible sequence that can be applied to another route set or urban area.

The input layer contains demand and operating variables that can be updated over time: passenger-flow estimates, observed running time, service headway, the number of buses assigned to a route, GPS/GNSS traces, dispatching observations, and electronic fare-collection records. Combining these sources improves temporal and spatial coverage compared with using a single source (Urbano et al., 2025).

The network is treated as a sequence of discrete states. A state may correspond to a route segment, stop, or transfer node, and each state has a limited set of feasible transitions. Candidate trajectories are generated from the origin to the destination through these admissible transitions. Dynamic programming is then used to track how a local choice at one stage affects the feasible and efficient choices available at subsequent stages.

Each candidate route is evaluated using a common set of service and operational criteria. In the present formulation, the core criteria are travel time, waiting time, headway, number of transfers, transport cost, service quality, and reliability. This set is not intended to be rigid: additional criteria, such as safety or environmental performance, can be introduced when the planning task requires them. The selected structure is consistent with the broader MCDM approach used in transport analysis (Ibarra-Rojas et al., 2015; Keshavarz-Ghorabaee et al., 2022).

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Table 1

Evaluation Criteria Used to Compare Bus-Route Alternatives

No.	Criterion	Operational meaning
1	Travel time	Total time required to move from origin to destination
2	Waiting time	Time spent waiting for the next available vehicle
3	Headway (service interval)	Elapsed time between two consecutive buses
4	Number of transfers	Number of vehicle changes required during a trip
5	Transport cost	Passenger- and operator-related costs associated with the alternative
6	Service quality	Regularity, convenience, and practical accessibility of the service
7	Reliability	Degree of agreement between planned and observed operation

The model is implemented through the following six-stage procedure:

Stage 1. Build the input dataset. Assemble passenger demand, observed running time, headway, fleet allocation, and route information in a common database.

Stage 2. Generate feasible alternatives. Construct all admissible route options between the selected origin and destination, subject to network constraints.

Stage 3. Calculate criterion values. Estimate travel time, waiting time, number of transfers, transport cost, service quality, and reliability for every alternative.

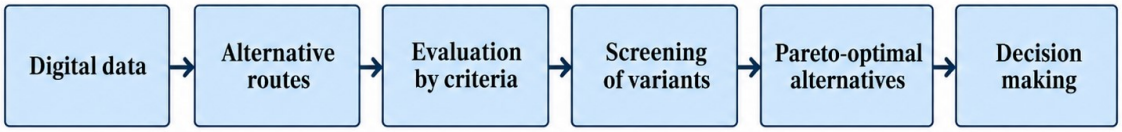
Stage 4. Remove dominated solutions. Exclude any alternative for which another feasible option is no worse on all principal criteria and better on at least one.

Stage 5. Form the Pareto-efficient set. Retain alternatives for which improving one criterion requires deterioration in at least one other criterion.

Stage 6. Make the planning choice. Compare the remaining efficient alternatives with passenger demand, available fleet capacity, and current management priorities.

Figure 1

Workflow for Screening and Selecting Route Alternatives



Uncertainty is handled by treating key inputs as updatable observations rather than permanent constants. When passenger demand, running time, or traffic conditions change, the affected criterion values are recomputed and the efficient set is regenerated. If expert-defined criterion weights are introduced, sensitivity analysis should be used to test how strongly the final ranking depends on those weights. Where uncertainty is substantial, fuzzy techniques can be added to the evaluation process (Alkharabsheh et al., 2022; Kilic & Demirel, 2025; Saaty, 1980).

Results. The analysis produced a route-selection framework in which operational feasibility and passenger-oriented criteria are assessed together. Its principal contribution is not a single numerical optimum but a structured way to narrow a potentially large set of route alternatives to a smaller group of efficient and practically defensible options.

First, the bus network was formalized as a sequence of connected decision states. This representation makes it possible to evaluate route trajectories incrementally: a choice made at one stage changes the set of feasible outcomes at later stages. Dynamic programming is therefore used as the mechanism for linking local route decisions to the final network outcome.

Second, the evaluation is extensible. The seven core criteria shown in Table 1 form the basic comparison set, but the model does not impose a fixed upper limit on the number of criteria. Safety,

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environmental performance, accessibility, or other locally relevant indicators can be added without changing the overall decision logic. This flexibility is consistent with MCDM applications in urban transport (Keshavarz-Ghorabaee et al., 2022).

Third, the model uses dominance screening before a final choice is made. Alternatives that are clearly inferior are removed, while nondominated alternatives are retained as the Pareto-efficient set. This avoids the misleading assumption that one route must be best in every dimension. Similar use of Pareto-based reasoning has been reported in integrated public transport scheduling and vehicle allocation (Liu et al., 2023).

Fourth, the model can be recalculated when new digital observations become available. The joint use of passenger-flow information, GPS/GNSS data, fare transactions, and dispatching records allows route performance to be revisited as conditions evolve rather than only during periodic manual reviews (Urbano et al., 2025).

Table 2

Decision Rule Used to Retain or Reject Route Alternatives

Alternative status	Interpretation	Action
Nondominated	Performs at least as well as competing alternatives across the principal criteria and better on at least one criterion relative to a dominated alternative	Retain
Dominated	Another feasible alternative is no worse on all principal criteria and better on at least one criterion	Remove
Pareto-efficient	No criterion can be improved without worsening at least one other criterion	Carry forward to final selection

Operational feasibility is checked after the efficient alternatives have been identified. The underlying dissertation relates the required fleet size to round-trip time and the planned service interval. If round-trip time is denoted by $T_{o\beta}$ and the service interval by I, the number of buses required on the route is:

$$A_m = T_{o\beta} / I$$

When the required number of buses, A_m, is known, the corresponding service interval is obtained from:

$$I = T_{o\beta} / A_m$$

These relationships provide a simple resource check: an alternative may be efficient in the multi-criteria sense but still be impractical if the available fleet cannot sustain the required headway. The complete decision chain can therefore be summarized as passenger demand → route alternatives → operational checks → multi-criteria screening → Pareto-efficient set → final planning decision.

Discussion and Conclusion. The findings reinforce the view that urban bus-route design should not be reduced to shortest distance or minimum travel time. A route may shorten in-vehicle time while creating additional transfers or higher operating costs; another may take slightly longer but provide more stable service or better coverage. The proposed framework makes these trade-offs explicit and allows passenger and operator interests to be considered within the same analytical process (Ibarra-Rojas et al., 2015; Keshavarz-Ghorabaee et al., 2022; Mandl, 1980).

A practical advantage of Pareto screening is that it preserves choice. Instead of presenting decision-makers with one mathematically imposed solution, the method returns a small set of efficient alternatives. The final selection can then reflect current fleet availability, demand patterns, policy priorities, or service-quality targets. This is consistent with recent work in which timetable and vehicle-allocation decisions are optimized jointly rather than independently (Liu et al., 2023).

The framework also has a clear limitation: the quality of the output depends on the quality of the inputs. Sparse GPS/GNSS records, incomplete fare data, or inconsistent dispatching logs can distort one

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or more criterion values. For operational use, the data streams should therefore be integrated and quality-checked (Mirzabekov & Kurbonova, 2025; Urbano et al., 2025). If criterion weights are used, their influence should be tested through sensitivity analysis; fuzzy methods can be added where uncertainty cannot be adequately represented by precise values (Alkharabsheh et al., 2022; Kilic & Demirel, 2025).

In summary, the proposed model provides a more realistic basis for route-network planning under uncertainty than a single-criterion approach. Dynamic programming connects decisions across successive network states, while Pareto analysis separates clearly inferior alternatives from those that represent meaningful trade-offs. For Nukus, periodic updates using passenger-flow, GPS/GNSS, fare-collection, and dispatching data would allow the route network to be reassessed as travel demand and operating conditions change.

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