Improvement of the system of bus routes in the conditions of expansion of the urban area (on the example of the city of Termez)

Azamjon Komilov [a)], Abdimurot Kuziev, Abobakr Muratov, Rustam Xudaykulov, Alisherjon Mirzaev

Termez State University of Engineering and Agrotechnologies, Termez, Uzbekistan

[a)] *Corresponding author:* azamjon.komilov88@gmail.com

Abstract. *This scientific article provides a comprehensive analysis of the improvement of the urban bus route system and timetable. The population growth, expansion of urban areas, establishment of new residential complexes, and social facilities have led to a sharp increase in demand for public transportation, particularly the bus system. The current network of routes and timetables fails to effectively accommodate the growing passenger flow. Therefore, there is a need to reconsider the existing routes, synchronize schedules in overlapping sections, redistribute passenger flows, and ensure efficient use of resources. The article presents a model developed through mathematical modeling based on graph theory, taking into account inter-route connectivity, the number of stops, travel intervals, and passenger flows. Based on the analysis conducted using Termez city as a case study, proposals have been made for reorganizing routes, optimizing service frequency, and reducing excessive vehicle congestion. This methodology contributes to the sustainable and efficient organization of the urban transport system, as well as improving environmental and economic indicators*.

INTRODUCTION

In recent years, due to the increase in urban population and the growth of automobile transport volume, the demand for public transportation systems has sharply risen. In particular, bus transport plays a vital role in meeting the mobility needs of the urban population as a primary mode of transit. However, the existing network of routes and schedules does not fully correspond to the continuously increasing passenger flow.

The expansion of urban areas, the formation of megacities, and urban agglomerations necessitate addressing the diverse social and cultural mobility needs of their residents. Historically, this issue has been addressed by organizing transportation services for the population in the city and adjoining areas using various modes of transport. Thus, the mobility of the urban population is ensured through transport movement [1, 2].

The aim of this article is to propose a scientifically grounded evaluation method for the optimal organization of bus transportation within urban areas, minimizing fuel consumption while managing movement between various locations and passenger flows. For example, by synchronizing bus schedules on overlapping route segments and restructuring routes using the potentials method, passenger waiting times can be reduced by 7-8%, and fuel consumption can be significantly decreased [3, 4, 10, 11].

In her research, O.A. Pitaleva [5] approached the issue from the perspective of the load level of the city's route transport network and the number of vehicles. The development of a new surface passenger transport route network involves the redistribution of passenger flows. The author notes that when the number of vehicles exceeds 1000, the load level increases. Adjusting the route scheme to evenly distribute vehicles across different sections of the road network helps reduce the load by 60%. S.A. Azemsha, in his works [6], proposes a methodology for determining the optimal movement intervals of route transport vehicles. This methodology takes into account the carrier's costs as well as passenger loss costs due to waiting times at stops.

The literature review indicates that numerous scientific studies focus on the development of public transportation and ensuring environmental sustainability. The reviewed research typically analyzes the technical and technological aspects of sustainable transport, enabling the identification of organizational issues, assessment of passenger flow irregularities, and proposals for their reduction [3, 5, 8, 12-40]. However, among the existing studies, a comprehensive evaluation methodology for urban bus transport-particularly approaches involving route restructuring, schedule synchronization, and resource redistribution at overlapping sections-is not clearly presented [13].

EXPERIMENTAL RESEARCH

Effective organization of bus routes within a city or region requires not only ensuring movement along existing routes but also their restructuring in coordination with each other and the overall transport infrastructure. Population growth, the development of new residential areas, and the geographical expansion of social facilities-such as schools, hospitals, markets, and workplaces-necessitate a reevaluation of the current bus routes.

By coordinating inter-route timetables and restructuring routes, it is possible to balance transport flow on overlapping road segments, reduce congestion, prevent excessive load, and ensure continuity of transport services. This process is especially important for creating efficient connections from newly densely populated areas to central and social facilities, providing proper service according to passenger flow, and optimizing the number of vehicles.

Within the framework of this methodology, the main task is to study the possibilities of re-routing urban bus lines based on theoretical models, harmonizing them with regional development, demographic changes, and the location of social infrastructure. This practically serves to create an efficient transport system, ensure the rational use of resources, and comprehensively meet the population's transportation needs.

At a minimum, it is possible to conduct an analysis considering the minimum distances between stops on each route and determine optimal solutions. Optimal solutions should include evaluating the distance between stops on each bus route, load levels during peak hours, service frequency of each route, bus capacity, service time at stops, passenger delivery time, and bus movement intervals. K.A. Shubenkova conducted research on the transportation processes in buses, including passengers arriving at stops, waiting for buses, dwelling at intermediate stops, boarding and alighting passengers, and time spent in congestion [9].

Objective function (minimum time)

$$min\ \sum_{(i,j)\in E} t_{ij} \cdot y_{ij} \tag{1}$$

Constraints:

1. Preservation of passenger flow (within the zones):

$$\sum_{j:(i,j)\in E} y_{ij} - \sum_{j:(j,i)\in E} y_{ji} = \begin{cases} P_i,\ if\ is\ the\ origin\ zone \\ -P_i, if\ is\ the\ destination\ zone\ \ \forall_i \in V\ , \\ 0,\ otherwise \end{cases} \tag{2}$$

That is, the balance of passenger inflow and outflow is maintained.

2. A transport route must exist:

$$y_{ij} \leq M \cdot x_{ij},\ \forall (i,j) \in E \tag{3}$$

If $x_{ij} = 0$, then there can be no passengers on this route.

3. The length of bus routes is limited (optional constraint):

$$\sum_{(i,j)\in E} x_{ij} \leq L_{max} \tag{4}$$

This helps prevent the bus route from becoming excessively long..

$y_{ij} \geq 0$ is the non-negativity constraint, meaning the number of passengers or the number of bus movements flowing through the edge (i,j) cannot be negative.

4. Potentials condition

Meaning of each element in the formula:

t_{ij} − travel time along the route from node i to node j, measured in hours;

y_{ij} −number of passengers transported along the route from node i to node j;

P_i − number of passengers at node i (e.g., in a residential area or zone);

$x_{ij} \in \{0,1\}$ - binary variable indicating whether the route from node i to node j is included in the bus network (1 if yes, 0 if no);

M_j- node j is a destination node (e.g., a social facility such as a school, hospital, or workplace).

This can be achieved using the graph theory method. In this approach, the model is structured such that transport routes or corridors are represented as vertices (nodes), while edges (connecting lines) represent the main connecting points.

$$G = (V, E) \tag{5}$$

V– edges (nodes) are considered as key points (addresses, terminals, stops) within the city area. Each node $v \in V$ can serve as a source, transit, or destination node.

$E \subseteq V \times V$ – represents the roads (routes), where each $(i, j) \in$ E indicates the existence of a path from $i\ to\ j$ (i.e., dedicated bus lanes).

For each road (edge) $(i, j) \in E$, t_{ij} denotes the travel time (or total cost: time, distance, or price).

The expansion of the city area of Termez necessitates a revision of public transportation routes and their adaptation to regional development and population growth. This is a key factor for optimizing the transportation system, effectively distributing passenger flow, and improving the quality of service.

In practice, the number of possible route scheme variants can be extremely large (combinatorial in scale). Therefore, in determining the optimal scheme, combinatorial analysis, mathematical modeling, and algorithmic approaches are used. The city of Termez is divided into 12 microdistricts (residential areas).

The number of bus routes is determined using the following formula:

$$m = [(\mathrm{n} - 1) \cdot \mathrm{n}]: 2 = [(12 - 1) \cdot 12]: 2 = 66 \quad (6)$$

here, m represents the maximum number of routes, and n represents the number of microdistricts.

The possible combinations of bus routes are represented by the formula $2^{(n-1)n} - 1$. This indicates that as the number of nodes (stations) increases, the number of combinations grows exponentially, highlighting the computational complexity of the problem.

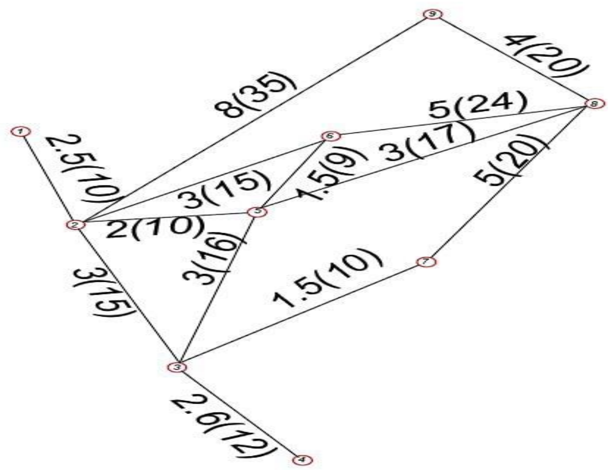

FIGURE 1. Transport network

The proposed methodology was applied to the analysis of passenger transportation as a practical case, resulting in a balanced distribution of traffic and passenger flow through the rerouting of transport services.

RESEARCH RESULTS

The considered example is represented by a conditional transport network (Figure 1). This network consists of:

Circular symbols in the transport network represent the centers of microdistricts within the city, each assigned a unique identifier. The arcs between the circles denote the bus routes, with the numbers between them indicating the travel time of the bus in minutes. Values given in parentheses represent the corresponding route lengths in kilometers.

Passenger flow data is provided based on Table 1, which expresses the approximate passenger demand between microdistricts (derived from statistical data and processed survey results).

Based on this table, necessary calculations were carried out for the formation and optimization of bus routes. The main objective is to ensure the efficient use of transport vehicles and to minimize the total travel time for passengers.

TABLE 1. Passenger flow

Where from	Where								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	-	358	152	112	189	183	345	253	198
2	289	-	221	156	289	153	187	241	95
3	235	158	-	112	336	148	215	356	201
4	251	189	83	-	194	211	156	245	158
5	349	210	189	156	-	192	194	215	125
6	189	389	201	199	125	-	89	174	102
7	356	275	189	193	341	121	-	349	101
8	346	389	323	112	359	123	245	-	98
9	125	189	298	123	101	79	79	56	-

Stages of Route Scheme Development. The development of a bus route scheme for an urban transport network is carried out in several key stages. Below, the stages of route scheme development are considered.

Stage I. *Determining the Shortest Paths Between Microdistricts by Time.* The problem of finding the shortest path is one of the classic pathfinding challenges, with numerous algorithms available. Among them, a simplified two-step approach close to E.V. Dijkstra's algorithm is applied in the following order:

a) Assigning a zero potential value to the initial node.

b) Determining the potentials of the nodes and finding the shortest path.

Stage II. *Formation of the Initial Route Scheme.* As the initial route scheme, routes are selected that include direct (i.e., through) and local (sectional) routes connecting several microdistricts. These routes must satisfy sufficient conditions for covering passenger flow.

A direct route is one that connects the centers of at least three microdistricts within the shortest possible time interval, ensuring movement without transfers (i.e., without changing buses).

This requirement is mathematically expressed as follows:

$$\frac{c \cdot q \cdot T_p}{\rho} \cdot \frac{1}{P_{ij}} \leq t_{n_l} \tag{7}$$

Here: c- coefficient of unevenness in passengers' arrival at the stop (accepted value: 0.5); q- capacity of the bus used (in our case, 38 passengers); T_p - selected time interval of the day (accepted value: 60 minutes); ρ-coefficient of unevenness of passenger flow per hour (assumed to be 1.1); P_{ij}-maximum passenger flow between nodes i and j (i.e., the number of passengers transported along the important route); t_{n_l}- minimal time, in minutes, required to deliver a passenger traveling via the route between points i and j to their destination.

If this inequality is satisfied, meaning the waiting time on the left side is less than or equal to the passenger transfer time on the right side, then the route is considered justified and efficient, and it is included in the route scheme.

Stage III. *Checking the Compliance of Routes with the Specified Travel Interval.* At this stage, only partial routes that do not directly match other routes but allow travel by bus through intermediate points were checked.

The travel time interval for bus movement along the route is determined by the following formula:

$$I_{ij} = \frac{q \cdot T_p}{P_{ij}} \tag{8}$$

Here: q bus capacity (38 passengers); T_p – daily transportation period (60 minutes); P_{ij}– number of passengers on the route.

Stage IV. *Determining the Feasibility of Organizing Additional Routes.* In addition to the main initial routes, the organization of additional "point-to-point" routes is envisaged to improve system efficiency.

According to this approach, the initial set of routes is assumed to be pre-existing. For each combination:

-a travel path is determined for all passenger flows based on the route scheme;

-the path requiring the minimum travel time for each passenger is selected;

-during this process, transfers and the time spent on them are also taken into account.

Stage V. *Checking the Utilization Factor of Bus Route Capacity.* To determine the practical efficiency of the accepted route scheme, the capacity utilization factor of buses across the entire network is evaluated.

If the average utilization factor across the network falls within the specified normative range (usually 0.7–0.9), the route scheme is considered practically acceptable.

Otherwise, it is necessary to either increase the number of routes or redistribute the passenger flow.

Stage VI. *Determining the Passenger Transportation Volume by Network Sections.* Calculating the feasibility of additional routes within the network sections.

Stage VII. *Construction of the Load Diagram.* Based on the obtained values, a graphical scheme of the passenger flow distribution within the network is constructed (Figure 2). It shows the maximum passenger flow values corresponding to each route segment; the numbers representing passenger flow loads (persons/hour) are placed over the arcs in the diagram. This diagram is important for identifying the most heavily loaded nodes of the bus network, allocating resources, and evaluating the efficiency of routes.

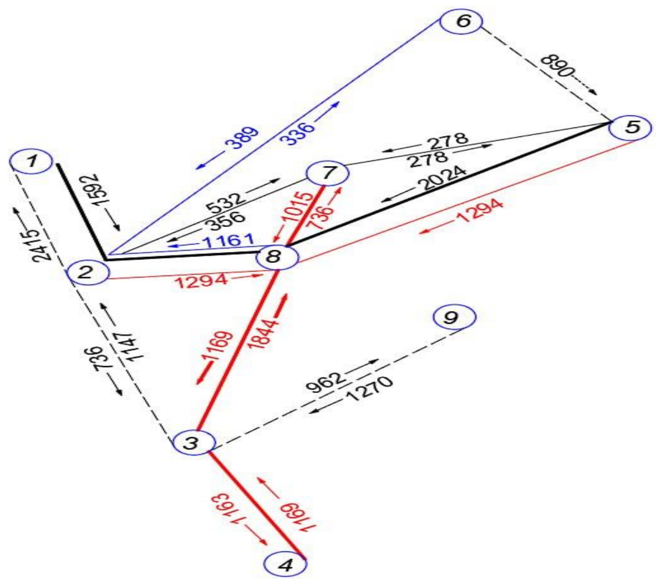

FIGURE 2. Route network with travel times and transfers

Stage VIII. *Distribution of Passenger Flows on Combined Routes.* If two or more routes pass through a certain network segment, the following procedure is applied:

1. The traffic density (i.e., passenger flow) on the combined route is analyzed separately for each individual route.
2. The route with the highest density on the combined route is selected and designated as the main route. The traffic flow along this route represents the total density.
3. For the remaining routes, their traffic density on the main route is analyzed, and a reduced traffic flow value is assigned. This value is subtracted from the largest total density passing through the combined route.

Finally, the passenger transportation volume on the last route is determined based on the difference between the maximum traffic density on this route and the total densities of the other routes.

A mathematical model based on graph theory has been proposed for the efficient organization of routes in the urban public transport system. In this model, the urban area is represented as nodes and edges, where each node corresponds to a stop or important point, and edges represent the connecting road segments.

The primary objective of the model is to ensure the delivery of passengers from source nodes to destination points with minimal time or minimal cost. A key constraint introduced is the conservation law of passenger flow, which maintains the balance between incoming and outgoing passengers at each node, thereby ensuring the physical realism of the transport system.

An advantage of the discussed model is its scalability to complex transport networks with a large number of stops and routes, while also possessing mathematically rigorous solution methods such as linear programming, the Bellman-Ford algorithm, and others.

Additionally, when applying the model in real conditions, the following factors should also be taken into account:

-Temporal variability of passenger flow.

-Maximum capacity of each road segment.

-Natural and social factors.

-Expansion of areas due to new constructions.

Overall, the proposed model plays a significant role in improving the efficiency of the transport system through route reorganization and optimization, ensuring quality and continuity of service for passengers.

CONCLUSIONS

During the study, a mathematical approach based on graph theory was developed to model passenger transportation processes and reorganize routes with the aim of optimizing the urban public transport system. In the model, the urban area is represented by nodes and edges, where each node corresponds to a stop or important transport point, and edges represent the road segments connecting them.

The primary objective of route planning is to deliver passengers from origin to destination with minimal time or cost, expressed through constraints such as the conservation law of passenger flow and synchronized movement of vehicles on overlapping routes.

The study results indicate that under conditions of urban expansion and increasing passenger density, it is necessary to review existing transport routes, distribute them rationally, and coordinate schedules. The proposed model enables the effective organization of vehicle movement in practice, reduces conflicts and excessive congestion between routes, and ensures efficient use of overall resources.

Applying the approach developed based on this model in cities experiencing territorial expansion, such as Termez, can improve the quality of the transport system, enhance the efficiency of passenger services, and optimize transport accessibility to social facilities.

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