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ABSTRACT

of the dissertation for the degree of Doctor of Sciences

DEVELOPMENT OF METHODS AND MODELS FOR INCREASING THE EFFICIENCY OF THE CITY BUS ROUTE NETWORK

Specialty: 3350.01- Management of transportation processes

Field of science: Technical sciences

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GENERAL DESCRIPTION OF WORK

The urgency of the problem and degree of research. In the cities of the Republic of Azerbaijan, especially in the city of Baku, bus transport takes on the majority of the total passenger traffic. Bus transport acts as both a means of direct delivery and a means of delivery to metropolitan and suburban railway lines. In almost all existing medium and large cities, the bus occupies an important place as public transport. Currently, the population of the city served by bus transport is significantly greater than the population served by other modes of transport. The large number of bus routes used in the city and the limited number of streets used require the development of new methods and models for improving the quality of bus routes and the transport network as a whole. Improving bus transport is possible through optimization and modeling of its operation according to various criteria. A model compiled taking into account the influence of various parameters, including operating modes of buses on the line, will improve the operation of the network and increase controllability.

Buses often move in the general flow, influenced by the general traffic intensity on the roads, controls, etc. There are deviations from the traffic schedule. Moreover, if we take into account the occurrence of additional time losses on coinciding sections, then the importance of modeling the operation of the bus route network taking into account these effects becomes more obvious.

In the direction of modeling the loss of time of passengers and the movement of vehicles in urban public transport, useful research was carried out by V.A. Gudkov, A.V. Velmozhin, M.E. Koryagin, I.V. Spirin, Yu.S. Ligum, A.P. Lopatin, M. E. Antoshvili, V. P. Fedorov, A. O. Arrak, A. N. Novikov, N. N. Danilov. The completed work shows that when optimizing the urban public transport system and modeling routes, the main factors are the interests of passengers and vehicle owners.

Modeling the operation of buses at stops was considered in the cases of W.Gu, C.Wang, J.Weng, B.Alonso, J.M.Bunker, S.Chien, I.Dakic, S.Mozzoni, Z.Ning, B. Bian, J. Gibson, W. Sun, J. Zhao, G. R. Bivina. These works mainly consider the issues of assessing the capacity of a bus stop, delays of buses at stops, the occurrence of conflicts at a stop, and creating models of queues before a stop.

The creation of a bus route network model can provide conditions for ensuring a unified approach to the bus route network in cities and its operational management in case of changes.

The "State Program for Road Safety in the Republic of Azerbaijan for 2019-2023" provides for the development of the existing public transport infrastructure, improvement of public transport, improvement of the quality of service in public transport and the implementation of measures to increase confidence in public transport.

Thus, the development of effective workable methods and models of the bus route network, compatible with existing restrictions, is an urgent scientific and practical task and is of national economic importance. Addressing these issues requires important conditions based on scientific research and innovation.

Object and subject of research. The object of research of the dissertation work is the city bus route network, bus stops along which a large number of bus routes and bus routes pass.

The subject of the dissertation is the quality of service in the bus route network, loss of time on bus routes, queues at stops.

Purpose and tasks of the work. The purpose of the dissertation work is to study and evaluate the parameters affecting the quality of service for passengers and the operation of buses on routes in order to increase the efficiency of buses, develop methods for assessing and reducing the loss of time of buses and passengers on sections of the route network and at stops, as well as methodology for assessing efficiency route network.

To achieve this goal, the following tasks are envisaged:

1. Preparing a model for estimating passenger time loss.
2. Determination of the main indicators affecting time loss on bus routes.

3.Assessment of the impact of bus operating modes on the overall traffic flow at stops organized in various ways.

4.Assessment of bus time losses on route sections.

5. Simulation modeling of the bus route network.

6.Development and testing of a model for coordinating the operation of bus routes with coinciding sections and stops.

7.Development of a method for assessing the efficiency of the route network.

Research methods. To solve the problems posed in the work, theoretical studies and simulation experiments were used. Probability theory and methods of mathematical statistics, Markov model and Kolmogorov equations were used for the study. Anylogic and PTV VISSIM simulation programs were used for simulation experiments. The research was carried out comprehensively, using a full-scale experiment, a simulation experiment and technical analysis.

Scientific statements submitted for defense:

1. The principle of assessing the loss of time of passengers within the traffic interval, including passengers who cannot get on the first bus that arrives at the stop.

2. Development of a mathematical model for assessing random stops that cause loss of time in front of traffic lights for the route network of city buses.

3. Development of a model for coordinating the operation of routes with grouping of traffic intervals to reduce the loss of bus time at stops.

4. Methodology for using multi-criteria decision-making methods when choosing buses for routes.

5. Development of a mathematical iterative model for regulating route schedules according to the time of arrival at a stop in order to reduce queues and delays of buses before a stop through which a large number of bus routes pass.

6. Development of a method for mathematical calculation of assessing the efficiency of buses on routes in accordance with local conditions, taking into account the number of passengers transported on sections of the route.

Scientific novelty of the research:

• A methodology has been developed and prepared for assessing the loss of time of passengers on the route, based on the operating mode of buses and the choice of boarding passengers on the bus.

• The influence and reverse influence of the bus traffic mode in the stopping area on the movement of traffic flow has been studied.

• A method has been developed for predicting lost time taking into account random delays along the route section.

• A methodology has been developed for coordinating the work of bus routes with common sections and stops.

• A methodology for creating a simulation model has been developed in the Anylogic program to simulate the sequence of arrival of buses at a stopping point on routes.

• An iterative method is proposed for organizing the order of arrival of buses of different routes at heavily used stops serving a large number of buses and justified using a simulation model.

• To assess the efficiency of buses on bus routes, an assessment methodology is proposed, based on taking into account the volume of bus transportation and the actual loss of time in the street network.

Theoretical and practical significance of the research:

• Determining the parameters that influence the loss of bus time on bus routes and the level of their influence on delays makes it possible to increase the accuracy of traffic schedules when planning work on the route.

• Planning the order of arrival of buses at heavily used stops, through which a large number of bus routes pass, significantly reduces the waiting time for buses at stops.

• The proposed methodology for assessing the effectiveness of a city bus route allows us to determine the development trend of the city bus route network over different periods.

• The results of the study of bus routes were presented to companies involved in bus transportation to the Azerbaijan Land Transport Agency.

As a result of reducing bus time losses at the selected stop, the annual economic effect expected from improving bus operation will be 446285 manats, and the annual economic effect expected from reducing passenger time losses will be 2735286 manats.

The work has prepared a theoretical basis for creating a model of the activity of the city bus route network. At the same time, the author formed the idea of the work, its purpose, basic scientific principles, scientific novelties, proposals for the application of the results of the work. The author has developed a methodology for assessing the operation of the bus route network, coordinating the work of buses at stops and creating a queue for the arrival of buses at stops at intensively used stops. The proposed mathematical and simulation models were tested in the virtual laboratory of the Institute of Logistics and Transport, on Baku bus routes. The text of the dissertation was presented personally by the applicant.

Approbation and application of research. The main scientific, theoretical and practical results obtained in the dissertation work were reported and discussed at conferences, symposiums and seminars at the international and national level:

At the conference organized at the Azerbaijan Technical University (Baku, 2013), at the international scientific and technical conference “Intelligent Technologies in Mechanical Engineering”, held at the Azerbaijan Technical University (Baku, September 28-30, 2016), at the Republican scientific and practical conference on the topic “Prospects for the development of the transport and road complex of the Republic of Azerbaijan”, organized at the Azerbaijan University of Architecture and Civil Engineering (Baku, December 14-15, 2017), at the scientific and practical conference on the topic “Azerbaijan in the international transport system: goals and prospects" organized at the Baku Engineering University (Baku, October 2-5, 2018), at the Republican conference on the topic "Transport of Azerbaijan: achievements, problems and prospects" (Baku, April 16-17, 2019), at the Republican scientific and technical conference “Technological prospects of the fourth industrial revolution: industrial Internet, cyber-physical systems and intelligent technologies”, dedicated to the 70th anniversary of the Azerbaijan Technical University (AzTU) (Baku, November 26-27, 2020), at the Republican scientific and practical conference on the topic

“Prospects for the development of the transport, road and logistics complex in the Republic of Azerbaijan" held at the Azerbaijan University of Architecture and Civil Engineering (Baku, December 2, 2022), at the 3rd international scientific and practical conference "Concepts for the Development of Society’s Scientific Potential" (Prague, 19 -November 20, 2022), at the International Scientific Conference “Construction Mechanics, Hydraulics and Water Resources Engineering” (CONMECHYDRO - 2023) (Dashkent, April, 2023), at the 6th International Scientific and Practical Conference “Scientific Trends and Trends in the Context of Globalization " (Umeå, Sweden, September 19-20, 2023).

The results of the dissertation can be applied in the educational process, in research work and in practice. The practical results of the dissertation work were implemented in the company MENLOQQ LLC, engaged in bus passenger transportation in Baku, and approved by the relevant act, as well as recommendations were given for other companies providing bus passenger transportation.

Published works. 24 scientific works have been published on the topic of the dissertation work, including 13 articles included in the list of the Higher Attestation Commission under the President of the Republic of Azerbaijan (7 of them in journals published in foreign countries, including 4 of them published in journals included in the Web of Science).

The organization in which the dissertation work was performed. The dissertation work was completed at the Azerbaijan Technical University.

The total volume of the dissertation, indicating the volume of structural sections. The dissertation consists of 282 pages of computer text, including an introduction, 7 sections, conclusions, including 33 pages with a list of references, 26 pages with applications and 1 page of abridgements. The volume of the introductory part of the dissertation is 22132, the volume of Chapter I is 51389, the volume of Chapter II is 68501, the volume of Chapter III is 53411, the volume of Chapter IV is 70477, the volume of Chapter V is 57184, the volume of Chapter VI is 29411, the volume of Chapter VII is 29238 marks, total volume - 376743 characters.

The dissertation includes 58 figures, 38 tables, a list of references of 293 titles and 21 appendices.

The introduction provides information about the relevance and degree of development of the dissertation topic, the purpose of the research, new methods for solving problems, the main provisions submitted for defense, the scientific novelty and practical significance of the dissertation, the scientific results, as well as the structure of the work, and the application of the research results.

The first chapter of the dissertation provides a review of existing research and modern methods used related to modeling and optimization of the route network of city buses, the operation of buses on the line, with simulation modeling of the operation of city bus routes, modeling the operation of the bus stop network, with research and improvement of the level of service for passengers in city bus network.

An analysis of the literature carried out in connection with modeling the operation of the city bus route network allows us to conclude that, although a lot of research has been carried out in this area, research in the direction of taking into account the needs of passengers when choosing rolling stock, coordinating the operation of buses in order to prevent traffic jams in front of bus stops, accounting for delays in front of traffic lights when passing a section of the route is insufficient.

The small number of studies on reducing stop density by incorporating bus schedules is poorly substantiated and unapplied. In addition, the calculation of time lost by buses when passing a section of the route is based only on empirical formulas and may not always be effective.

Research shows that the level of satisfaction with the activities of public transport is specific for each city, depending on the density of the transport network, the characteristics of the services provided, the mental characteristics of the population, etc. Depending on, it may vary depending on the region, population and age of the population. Therefore, for each city it is necessary to study the opinions of public transport users about its activities, to model and optimize the route network in this direction.

Thus, it is necessary to model the operation of the bus route network from the point of view of reducing temporary losses of passengers, reducing bus delays at stops, and predicting bus travel times on route sections.

The second chapter is devoted to identifying directions for solving problems of public transport in large cities based on a logistics approach, analyzing the main problems that arise in the logistics management of urban public passenger transport and the operation of urban public transport, determining the main quality indicators on routes and methods for their assessment.

Improving the quality of public transport service in cities is one of the main solutions to ensure the normal operation of the city’s transport network from a logistics point of view. Upcoming measures that must be taken in this area include the selection and use of rolling stock in public transport that meets current standards and requirements, coordination of the operating mode of the network of public transport modes, and reducing the dependence of the operation of bus routes on traffic flow.

A logistics approach to the provision of transport services to the urban population by route transport requires the creation of a chain “transport enterprise (fleet) – passenger (consumer)”. The consumers in this process are mainly passengers and, in a certain sense, job owners. The logistics approach to urban passenger transport assumes full satisfaction of the needs of passengers (consumers).

The essence of using logistics in passenger transportation is to optimize the activities of transport operators and transport infrastructure. Vehicles arriving at the stop on time, a high-level information system, and ease of transition from one route to another are indicators of the quality of the passenger transport logistics system.

The main task of logistics in the urban passenger transportation market is to maximally match the potential market opportunities with the needs of passengers. The problems facing the logistics system of urban passenger transport can be divided into four main areas: management, transport, information, and organizational. Figure 1 shows a technological diagram of the process of urban passenger transportation[1].

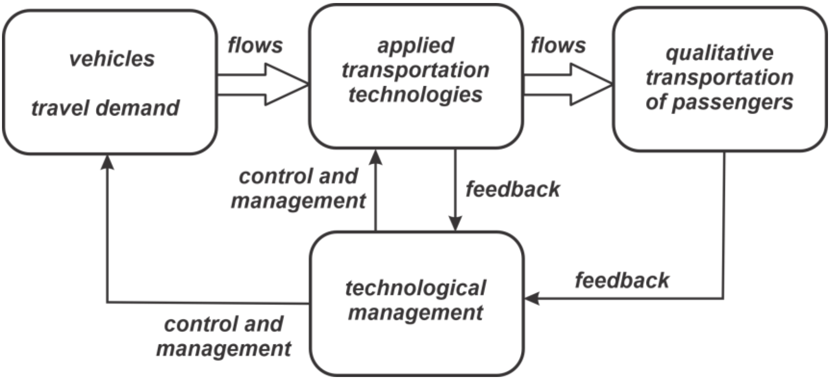

Figure 1. Technological diagram of urban passenger transport

One of the main features of driving on a bus route is that travel time and idle time on the route almost always deviate from nominal values, despite the fact that they are planned in advance by the schedule. Consequently, these parameters obey a certain distribution law. Experimental studies show that the speed of movement in the area between stops obeys the normal law:

$$f(v) = \frac{1}{\sigma(v) \cdot \sqrt{2\pi}} \cdot e^{-\frac{(v-M(v))^2}{2\sigma^2}} \quad (1)$$

Where; $M(v)$ - is the mathematical expectation; $\sigma(v)$ - standard deviation.

The longer the route section, the faster the bus travels through this section. As a result of the influence of various parameters, the technical speed value on the same section of the same bus route in the forward and opposite directions may differ significantly from each other. This means that the travel time for a section of the route changes. The distribution of technical speed values of buses in the direction of Gara Garayev Avenue and Muhammad Hadi Street in

[1] Пассажирские автомобильные перевозки: Учеб ник для вузов /Гудков В.А., Миротин Л.Б., Вельможин А.В. [и др.] - М.: Горячая линия-Телеком, - 2006. - 448 с.

the section between the H. Dostlugu and Akhmedli metro stations on bus route No. 62 in the city of Baku is shown in Figure 2 (a, b).

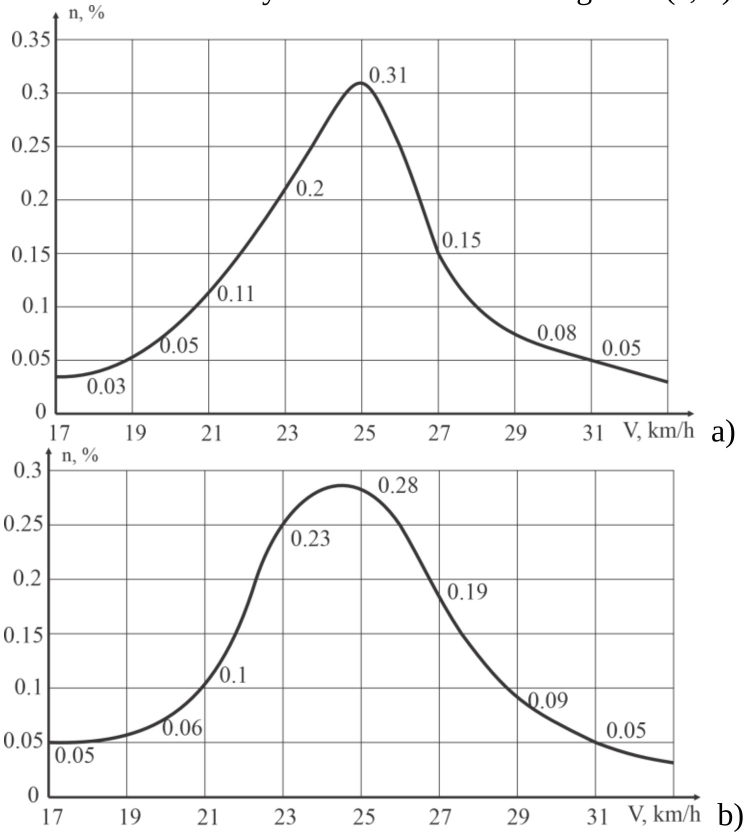

Figure 2. Distribution of technical speed of buses on the considered section of route No. 62 (forward and reverse)

As can be seen from Figure 2, the technical speeds of buses on the section of the route under consideration are distributed differently in forward and opposite directions.

A comprehensive assessment of the quality of transport services can be carried out using two methods: additive and multiplicative[2]. The additive score is determined by the following formula:

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[2] Галабурда, В.Г., Управление транспортной системой: учебник / В.Г.Галабурда, Соколов Ю.И., Королькова Н.В. - Москва, ФГБОУ «Учебно методический центр образования на ЖТ», - 2016. - 343 с.

$$K_{um} = \sum_{i=1}^{n} K_i \alpha_i = K_1 \alpha_1 + K_2 \alpha_2 + \ldots + K_n \alpha_n \quad (2)$$

Where; α_i - is the share of individual indicators in the system, $\sum \alpha_i = 1$.

The multiplicative estimate is determined by the following formula:

$$K_{um} = \prod_{i=1}^{n} K_i^{\alpha_i} = K_1^{\alpha_1} K_2^{\alpha_2} \ldots K_n^{\alpha_n} \quad (3)$$

According to the multiplicative assessment, if the weight of one indicator is equal to zero, the quality of the entire service will be equal to zero, that is, the service is not provided.

According to the traditional approach to bus routes, the main indicators of service quality are considered to be the regularity of buses along the route and the accuracy of the schedule. These indicators are easier to quantify. However, in many cases, passengers on bus routes, in addition to wasting time, give preference to comfort and safety parameters.

To accurately assess the quality of passenger service, it is necessary to interconnectively study the degree of bus congestion, travel time, regularity of traffic on the line, and passenger safety during the trip.

It should be noted that to determine the level of satisfaction of demand associated with the quality of passenger service, it may be more effective to study the attitude of the consumer himself, i.e. passengers' attitudes towards service quality. Currently, the use of electronic means of determining passenger claims is widespread and does not require large resources.

The third chapter of the dissertation is devoted to determining the level of use of bus routes in the city of Baku, studying the attitude of users of bus routes to these services, as well as analyzing the possibilities of creating a network of fast routes in the city, and developing a methodology for selecting rolling stock in accordance with the needs of passengers on city routes.

In September and October 2022, surveys were conducted covering all districts (13 districts) of the city in order to assess the population's attitude towards bus services in a comparative manner with other types of public transport. During the survey, conducted among 506 respondents, 40 questions were included in the questionnaires. The coverage of the bus route network and respondents' opinions regarding the creation of an alternative high-speed public transport network were studied.

The respondents were divided into 5 age groups (18-25, 26-35, 36-45, 46-55, 56-65). 67.8% of the respondents were men (343 questionnaires), 32.2% were women (163 questionnaires).

The population of Baku mainly uses four types of transport. These are buses, subways, taxis and commuter electric trains. The share of the population using public transport is shown in Figure 3.

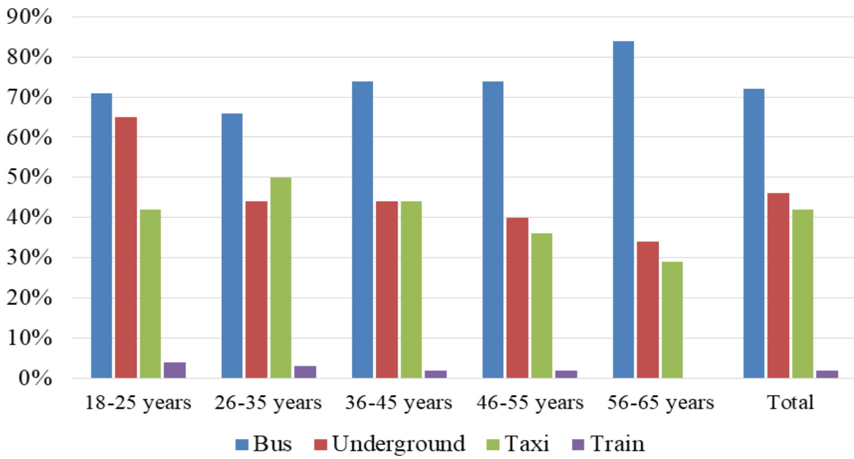

Figure 3. Proportion of population using public transport

As can be seen from Figure 3, 72% of passengers use regular bus routes, 46% use the metro, 42% use taxis and only 2% use trains.

The results of the study show that passengers prefer a certain type of transport for various reasons (Table 1).

Table 1.
Reasons why passengers prefer one type of transport or another

Reason for preference	Bus	Metro	Taxi
Availability	18%	13%	10%
High delivery speed	6%	36%	17%
Price (Tariffs)	10%	5%	4%
Convenience	15%	21%	37%
Proximity to workplace	17%	6%	4%
Safety	1%	0%	1%
COVID-19 pandemic	1%	0%	10%
Proximity to place of residence	31%	14%	2%
Save time	1%	5%	6%
Traffic jams on other modes of transport	0%	0%	9%

The main reason for choosing regular bus routes for traveling around the city of Baku is the proximity of bus stops to their place of residence (31%) and place of work (17%).

37% of respondents consider bus transport a dangerous mode of transport. 47% of passengers are dissatisfied with bus transportation in general. The most important reasons for passengers' dissatisfaction with bus transport are overcrowding of buses (37%), buses being late to stops and long intervals (21), the use of old and unsuitable buses on routes (16%), and unprofessional behavior of drivers (12%).

According to 76% of passengers who took part in the survey, the most noticeable disadvantage of bus passenger transport in Baku is the use of old buses. 37% of respondents believe that by using special lanes in Baku, they will get to their destination faster, and 33% believe that the creation of specialized lanes for buses will not affect the operation of routes.

Although respondents do not consider riding existing bus routes dangerous, the vast majority of them (67%) consider safety to be the main indicator of the quality of transportation (Figure 4). 55% of respondents consider delivery times to be an indicator of the quality of service, 42% - the professional level of drivers, 38% - ride comfort, 37% - the internal cleanliness of the car.

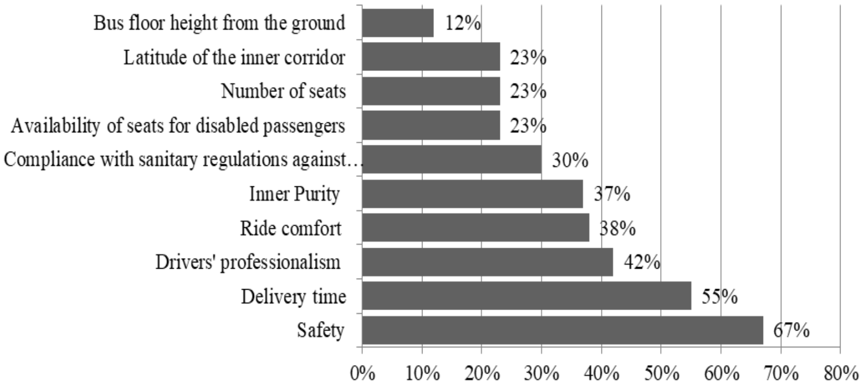

Figure 4. Preferred indicators of bus service quality

According to the survey results, the distance from the place of residence to the stop for 62% of the population is 50-200 m, for 24% - 200-400 m, for 8% - 400-500 m.

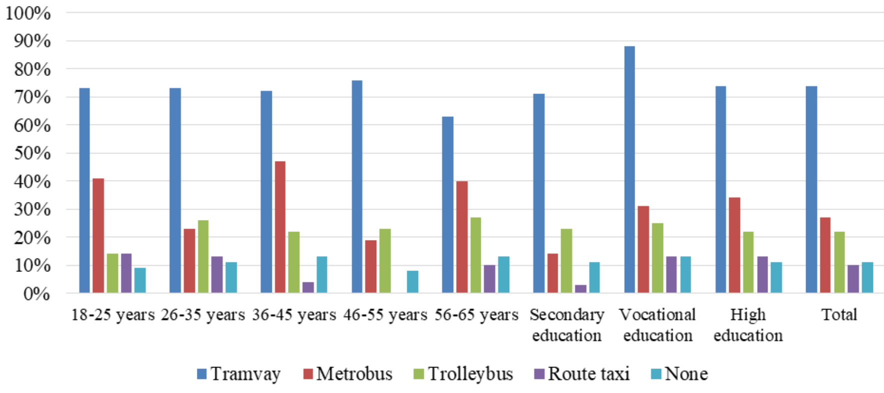

Figure 5. Distribution of opinions regarding the feasibility of using alternative public transport in Baku

As can be seen from Figure 5, the vast majority of respondents consider it appropriate to use alternative public transport in Baku.

According to the survey results, 27 percent of the city's population consider it advisable to use the metrobus (bus rapid transit).

It is necessary to assess demand when establishing routes for any type of public transport. The high-speed bus passenger transportation system is a modern and high-quality urban public transport system, formed as a result of the creation of infrastructure on a specialized strip, the organization of high-level passenger service and the provision of regular services. The capital investment for high-speed bus transport is significantly less compared to rail transport. Based on calculations, it has been determined that the creation of high-speed bus transport infrastructure in cities requires 4-20 times less funds than tram and light rail transport, and 10-100 times less than the metro[3].

It is possible to form a network of high-speed bus transport system passing through the main highways of Baku. The roads along which the main passenger and transport flows in the city of Baku are observed are Nobel Avenue, Heydar Aliyev Avenue, Babek Avenue, Dar Nagul Road. In the city of Baku, it is possible to create high-speed bus services on the following routes, the streets of which have more than three lanes:

-Option I:route through Nobel Avenue, Zig village - 20th area, route Surakhany village - Khirdalan city along the Darnagul road;

-Option II: route along Babek Yeni Gunashli Avenue - 20th area, route along the Darnagul road, Surakhani village - Khirdalan city.

The choice of rolling stock for route transport is mainly related to the correct determination of its capacity. When choosing rolling stock, it is very important to determine an option that reflects the interests of the parties, and in connection with this, a selection methodology that ensures the competitiveness of carriers in the market and takes into account the needs of passengers. It may be useful to use a combination of multi-criteria decision-making

[3] Скоростные автобусные перевозки. Руководство по планированию / Институт политики транспорта и развития. Нью Йорк. - 2007. - 279 с.

methods such as AHP (Analytical Hierarchy Process) and TOPSIS (Testing Excellence Based on Similarity to Ideal Solution).

The AHP method is based on checking the consistency index. If n elements are compared, a matrix A with size $n \times n$ is first created.

The consistency factor is calculated as follows [4]:

$$CR = \frac{CI}{RI} \quad (3)$$

Where CI - is the sequence index (n) of matrix A and is calculated as follows:

$$CI = \frac{\lambda_{\max} - n}{n-1} \quad (4)$$

In formula (3) is the index of the random sequence RI of matrix A and is taken from Table 2.

Table 2. Random sequence index values of matrix A

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0,52	0,89	1,11	1,25	1,35	1,40	1,45	1,49

If $CI \le 0.1$ the sequence index is accepted. Otherwise, the consistency index will be too high and the decision maker will have to re-evaluate the elements a_{ij} of matrix A to find a better consistency. The value $\lambda_{\max}$ is found from $A\overline{w} = \lambda_{\max}\overline{w}$.

The TOPSIS method is based on the logic of finding the best solution closer to the ideal positive and far from the ideal negative. Options are ranked based on indices calculated by distance from the ideal solution.

Multicriteria methods AHP and TOPSIS were used to select buses on routes No. 140,156,551,567 in the city of Baku. The most suitable one was selected among four buses (ISUZU HC-40 (capacity 45 people) DAEWOO 090 NEW (capacity 60 people) Karsan Atak (capacity 59 people) Otokar Doruk LE (capacity 49 people),

[4] Teknomo K. Analytic Hierarchy Process (AHP) Tutorial / K.Teknomo. – Revoledu, - 2006. - 20 p.

corresponding to the specified capacity (45-60) on the routes in question.

A comparison matrix showing the proposed criteria and their degree of preference over each other is given in Table 3.

Table 3. Collation matrix based on compared criteria

	Bus price	Fuel consumption	Novelty of the model	Floor height
Bus price	1	1	3	5
Fuel consumption	1	1	3	3
Novelty of the model	0.33	0.33	1	1
Floor height	0.2	0.33	1	1
Total:	2.53	2.66	8	10

Since, as a result of calculations, the resulting consistency index value corresponds to the requirement CI=0.009<10, the severity of the criteria can be used in the TOPSIS method. First, a normalized rank matrix is constructed, then the weights are integrated with the ranks, a weighting and normalization matrix is constructed, and positive and negative ideal solutions are found. Based on the results of the report, the options that are closest to the best and farthest from the worst are shown in Table 4.

Table 4. Identification of options that are close to the best and far from the worst.

	SI+	**SI-**
Karsan Atak	0.03763586	0.343710068
Otokar Doruk LE	0.342786747	0.04541839
Daewoo	0.070689516	0.308156588
İsuzu HC-40	0.056973833	0.296523527

Finally, ranking is carried out based on the indicator values and the most efficient bus is determined (Table 5).

Table 5. Selection of the most suitable bus based on indicator values

Indicator value	Rank
0.901307823	1
0.116995851	5
0.813408359	3
0.854460975	2

As a result of calculations, it was established that among those considered, the most suitable vehicle for use on routes 140, 156, 551, 567, providing passenger transportation services, is the Karsan Atak bus.

The fourth chapter of the dissertation is devoted to the study of the impact of the operation of the bus route network on the loss of time of passengers, traffic flows, and buses on routes. This chapter provides factors that cause bus delays on route sections and a model for predicting delays caused by the influence of traffic lights on route sections.

Passenger delays can vary significantly depending on network elements and bus service intervals. The probability of route passengers boarding the bus at the time of arrival at the stop can be determined as follows:

$$p_z = \frac{t_{stop,k}}{\dot{I}_k} \quad (5)$$

Where; $t_{stop,k}$ - bus stop time on the route k ; $\dot{I}_k$ - interval of buses on the route k .

According to Bernoulli's formula, the probability of boarding a bus number S of passengers S from route number k at the moment of arrival at the stop:

$$P_{s,S} = C_S^s p_z^s q^{S-s} \quad (6)$$

The most likely value S will be an integer from the interval $Sp + p - 1 \leq s \leq Sp + p$.

For all routes passing through a specific stop, the number of passengers remaining at the stop after m number of buses arriving at the stop at time t can be determined as follows:

$$A_t = A_{t-1} + C_{t-1;t} - (\sum_{j=1}^{m} b_j - \sum_{j=1}^{m} s_j) \qquad (7)$$

Where A_{t-1} is the number of passengers waiting at the stop from $t-1$ period, $C_{t-1;t}$ is the number of passengers coming to the stop during $t-1;t$ interval; $\sum_{j=1}^{m} b_j$ is the number of passengers getting on the bus j during t moment; $\sum_{j=1}^{m} s_j$ is the number of the passengers coming to the stop during t moment and getting on j bus. $j = 1...m$ is the number of passengers coming to the stop at t moment. For the stop through which pass n number route, we may write:

$$A_t = \sum_{i=1}^{n} a_{i,(t)} \qquad (8)$$

$$A_{t-1} = \sum_{i=1}^{n} a_{i,(t-1)} \qquad (9)$$

$$C_{t-1;t} = \sum_{i=1}^{n} c_{i,(t-1;t)} \qquad (10)$$

Where $a_{i,(t)}$ is the number of passengers waiting for route i during t moment and $a_{i,(t-1)}$ is the number of passengers waiting for route i during $t-1$ moment and $c_{i,(t-1;t)}$ is the number of passenger coming to get on the bus of route i during $t-1;t$ interval.

It is proposed to calculate the average time a passenger waits for a bus at stop z [5]:

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[5] Антошвили, М.Е. Оптимизация городских автобусных перевозок / М.Е. Антошвили, С.Ю.Либерман, И.В.Спирин. - М.: Транспорт, 1985. - 102 с.

$$\overline{T}_{g\ddot{o}z} = \frac{\dot{I}}{2} + \frac{\sigma_z^2}{2\dot{I}} + P_{meyl,z}\dot{I} \qquad (11)$$

Where σ is the standard deviation from the movement interval.

However, it is expedient to determine the time losses of passengers at each interval $t-1;t$:

$$T_{itki(t-1;t)} = t \cdot \sum_{i=1}^{n} a_{i,(t-1)} + \frac{t}{2} \cdot \sum_{i=1}^{n} c_{i,(t-1;t)} \rightarrow \min \qquad (12)$$

During tests carried out using a simulation model built in PTV VISSIM, the values of delays in traffic flow on a section of road 2600 meters long were determined as a result of bus maneuvers at a stop. The delay times of traffic flow in 2, 3 and 4 lanes were estimated. lane road with different frequencies of bus arrivals at the stop for different forms of organization of the stop in relation to the road.

According to speed limits in cities, the permitted speed of traffic flow is 50 km/h. An assessment of the loss of time in the stopping area created in the transport pocket shows that with a stable frequency of bus arrivals at the stop, when the intensity of traffic flow decreases from 800 vehicles/hour to 1400 vehicles/hour. the time it takes to cover the distance under consideration does not change significantly. And with constant values of traffic flow intensity, increasing the frequency of bus arrivals at a stop from 80 buses/hour to 180 buses/hour, the time to cover the distance under consideration changes significantly.

Delays in traffic flow when organizing a stop near the sidewalk are even more important. This increase in delays is even more pronounced with a small number of lanes. Increasing the frequency of bus arrivals at a stop organized in a “pocket” also increases the delay in traffic flow. However, an increase in traffic flow does not have a serious impact on this growth. The time it takes to pass through the stop zone at all values of traffic flow intensity, both when organizing a stop in a pocket and on the side of the sidewalk, increases with the increase in the frequency of buses arriving at the stop.

In Fig. Figure 6 shows the effect of the frequency of arrival of buses at a stop organized on the side of the road on the time the traffic flow passes through the section under consideration at a traffic flow intensity of 800 vehicles/hour.

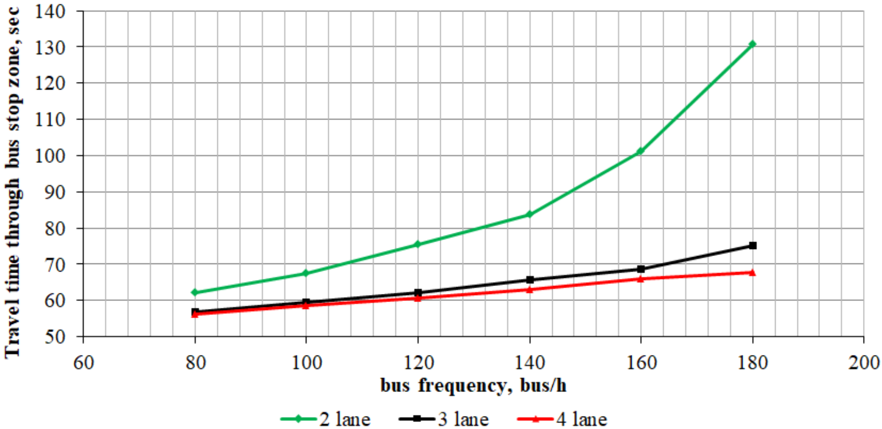


Figure 6. The influence of the frequency of bus arrivals on the time it takes to pass through a stop zone organized on the side of the road with a traffic flow intensity of 800 veh/h

As can be seen from Figure 6, an increase in the number of traffic lanes seriously affects the time it takes for traffic flow to cover the distance under consideration passing through the stopping area near the side of the road. Traffic delays on a two-lane road increase dramatically as the frequency of buses arriving at a stop increases.

Increasing the number of lanes for traffic flow passing through a stopping zone organized in a “pocket” does not have a significant impact on the time it takes the traffic flow to travel the distance under consideration at different values of bus arrival frequency (Fig. 7).

The results obtained using the simulation model created in PTV VISSIM show that increasing the frequency of buses significantly increases the delay time of traffic flow when buses move in the general flow. However, as the number of lanes increases, this effect decreases somewhat.

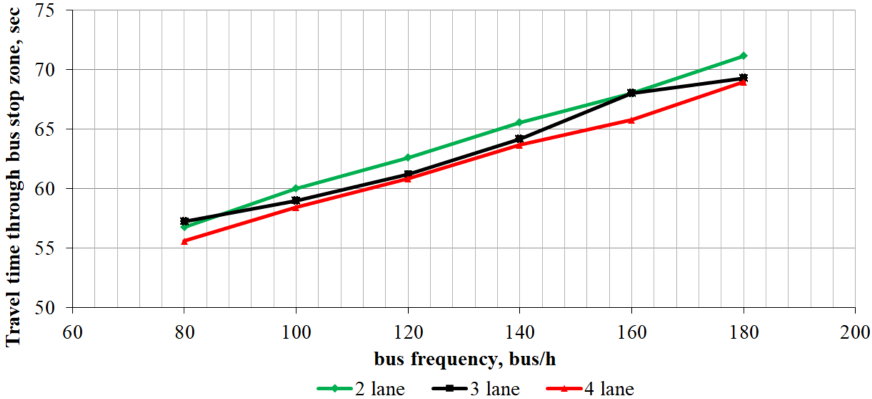


Figure 7. The influence of the frequency of arrival of buses at a stop in a "pocket" on the time it takes to travel the distance under consideration at a traffic flow intensity of 800 vehicles/hour

Measurements carried out on bus routes in the city of Baku assessed the impact on the speed and time of buses on the route of the degree of bus congestion, the intensity of traffic flows on the streets from which the route passes, the technical condition of the buses, the condition of the road, and the driver-car system.

When determining the effect of increasing bus filling on the bus travel time, the minimum ($\gamma = 0$) and maximum ($\gamma = 1$) values of the bus speed were taken into account. The measurement results show that increasing the filling of the bus increases the turnaround time of the bus along the route. At low bus speeds along the route, the effect of increasing bus filling on the bus turnaround time becomes more noticeable.

The traffic intensity values on the streets from which the route passes were taken into account based on the road load level ($z = 0...0{,}25$, $z = 0{,}25...0{,}5$, $z = 0{,}5...0{,}75$, $z = 0{,}75...1{,}0$). When a dedicated bus lane is not provided, the bus moves in the general traffic flow and thus becomes traffic dependent.

When taking into account the technical condition of buses, the condition of new buses is considered to be very good, and the technical condition of old buses is considered to be satisfactory, and traction characteristics are taken as a basis. Based on the values obtained as a result of the measurements, we can say that regardless of the brand and design of buses, if their technical condition is poor, the turnaround time of buses on the route increases.

When taking into account road conditions, cases were compared when the road had a dry ($\varphi = 0{,}75$) and wet asphalt ($\varphi = 0{,}35$) surface. Traffic safety on buses largely depends on the coefficient of adhesion between the tire and the road. Measurements show that the travel time of a bus in slippery road conditions is higher than in dry road conditions.

Table 6 shows the effect of longitudinal slope on the time taken by the bus. As can be seen from the table, the travel time of the DAEWOO BS 212 bus increases by 40% when the longitudinal slope of the road changes by 5 degrees and by 99% when it changes by 15 degrees.

Table 6. The influence of the longitudinal slope of the road on the bus travel time

№	Bus type	Travel time, min			Percentage increase in travel time	
		Longitudinal slope of the road			Increasing the slope	Increasing the slope
		$\alpha = 0$	$\alpha = 5$	$\alpha = 15$	$\alpha = 0 \rightarrow 5^0$	$\alpha = 0 \rightarrow 15^0$
1	DAEWOO BS 212	41.8	60.6	83.2	45	99

When the length of the route section increases from 0.35 km to 2.65 km, and the time of movement at a constant speed is about 37% of the total time of movement at the minimum speed, 29% at the maximum speed and 31% at the average speed.

It was revealed that the length of service, age of drivers and road lighting conditions also influence the time a bus travels along a route.

To properly plan the movement of buses along the route, it is important to determine in advance their possible loss of time. Estimating time losses while moving along a route is also effective from the point of view of improving the quality of passenger service.

The time lost by bus A on route M can be calculated as follows:

$$Lt_{AM} = \sum_{i=1}^{n} t_{bsi} + \sum_{j=1}^{m} t_{tlj} + \sum_{k=1}^{r} t_{nki} \qquad (13)$$

Where t_{bsi} - bus stop time at the bus stop i; t_{tlj} - bus delay time at a controlled intersection j; t_{nk} - traffic time in the area k.

The delay of buses at a specific traffic light site is random and depends on the operating mode of the traffic light at a specific intersection. The probability of a bus delay at an intersection with traffic lights is determined as follows:

$$p_{dbi} = \frac{t_{gi}}{T_{trci}} \qquad (14)$$

Где t_{gri} - продолжительность запрещающего сигнала светофора i; T_{trci} - продолжительность одного рабочего цикла светофора в рассматриваемом направлении, сек.

The average bus delay time at the observed intersection can be determined by the duration of the prohibiting signal, based on the formula for the probability of a bus delay (14). However, it is useful to create a forecasting model to take into account lost time at intersections when scheduling buses. The movement of a bus along a route can be divided into times of acceleration, constant speed and braking. Figure 8 shows several possible scenarios for the travel time of buses along the section of the route where 4 traffic light objects are located.

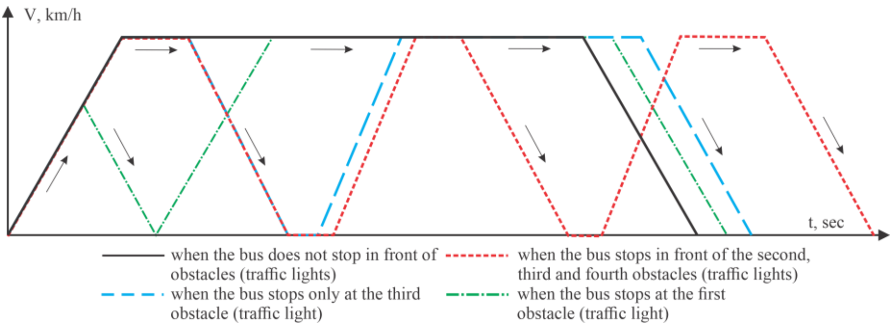


Figure 8. Scenarios for bus movement on a route section with 4 traffic light objects

If we denote by A the event of a bus delay at a traffic light, then the probability of a bus delay at at least one of the traffic light objects located in the route section will be calculated as follows:

$$P(A) = 1 - \frac{t_{y1}}{T_{trc1}} \cdot \frac{t_{y2}}{T_{trc2}} \cdot \frac{t_{y3}}{T_{trc3}} \cdot \ldots \cdot \frac{t_{yn}}{T_{trcn}} \quad (15)$$

Where t_{yi} - duration of green light at a traffic light object i.

If a section of the route belongs to one street and the "green wave" mode is applied on this street, then the probability of bus delays at intersections will be equal to the probability of delay at the first traffic light on this section:

$$P(A) = 1 - \frac{t_{y1}}{T_{trc1}} \quad (16)$$

Deviation of bus routes from the schedule beyond a certain limit is not considered appropriate. Therefore, it is important to predict real time losses before scheduling buses.

In the city of Baku 10 along Rashid Behbudov Avenue there are 3 traffic light objects, on one section of route 88 along the same avenue there are 4 traffic light objects, on one section of route 18 along Bulbul Avenue there are 4 traffic light objects. The process of delaying buses at traffic light objects on certain sections of the bus route can be considered as a Markov process. On a section of the route where 4 traffic light objects are located, possible options for bus delays can be shown schematically, as in Figure 9.

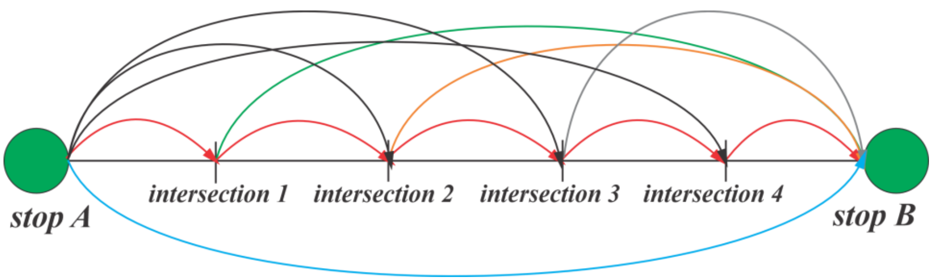


Figure 9. Scheme of possible options for delaying buses at traffic lights when passing a section of the route

Options for bus delays at traffic lights on the route section under consideration can be determined using combinatorics as follows:

$$C_n^k = \frac{n!}{k!(n-k)!} \tag{17}$$

The transition probability matrix between states will be as follows:

$$P = \begin{vmatrix} P_{1-1} & P_{1-2} & \dots & P_{1-16} \\ P_{2-1} & P_{2-2} & \dots & P_{1-16} \\ \dots & \dots & \dots & \dots \\ P_{16-1} & P_{16-2} & \dots & P_{16-16} \end{vmatrix} \tag{18}$$

From the point of view of obtaining the minimum delay time for buses, the ideal case is ( ) when buses are not delayed at any traffic light facility. When applying a normal regulatory regime, the probability of such a situation can be calculated as follows:

$$p_{d0} = \left(1 - \frac{t_{g1}}{T_{trc1}}\right) \cdot \left(1 - \frac{t_{g2}}{T_{trc2}}\right) \cdot \left(1 - \frac{t_{g3}}{T_{trc3}}\right) \cdot \left(1 - \frac{t_{g4}}{T_{trc4}}\right) \tag{19}$$

The probability of delay (situation S_2) only at the 1st traffic light will be determined as follows:

$$p_{d1} = \frac{t_{g1}}{T_{trc1}} \cdot \left(1 - \frac{t_{g2}}{T_{trc2}}\right) \cdot \left(1 - \frac{t_{g3}}{T_{trc3}}\right) \cdot \left(1 - \frac{t_{g4}}{T_{trc4}}\right) \tag{20}$$

Vehicles can move from state S_2 to state $S_6, S_7, S_8, S_{12}, S_{13}, S_{14}$ and S_{16} along a route segment. Therefore, when constructing the transition matrix, we accept the following condition:

$$P_{ij} = \Pr\{A_{n+1} = j \mid A_n = i\} = \begin{cases} 0 & i \geq j \\ p_{i,j} & i < j \end{cases} \tag{21}$$

Where A_{n+1} number of buses at the state j, A_n – number of buses at the state i.

If all intersections on a route section are regulated by traffic lights, then based on the operating modes of the traffic lights, the probabilities of buses transitioning between the indicated states can be calculated as follows:

$$P_{di\to dj} = \begin{cases} \prod_{j+1}^{n}\left(1-\frac{t_{qj}}{T_{trcj}}\right) & i=j,\ i=0,1,\dots,n \\ \frac{t_{qj}}{T_{trcj}}\prod_{j+1}^{n}\left(1-\frac{t_{qj}}{T_{trcj}}\right)\Big/\left(1-\frac{t_{qj}}{T_{trcj}}\right) & i=0,\ j=1,\dots,n \\ 0 & i\neq j, i\neq 0 \end{cases} \quad (22)$$

$$P_{di\to dj,\dots,dn} = \begin{cases} 0 & i\neq j, i\neq 0 \\ \prod\frac{t_{qj}}{T_{trcj}}\prod\left(1-\frac{t_{qj}}{T_{trcj}}\right) & i=0\ ve\, ya\ i=j \end{cases} \quad (23)$$

Delays at intersections with traffic lights on a route section are caused by buses hitting a prohibiting traffic light, and we consider this process as a Markov chain of discrete events. Here we take the discrete state of the system as a random variable. We consider bus delays at traffic lights as discrete cases. For a time-continuous discrete Markov process, the probability of finding the r th step of the system in any situation S_i is determined as follows:

$$p_i(r) = P[S(r) = S_i];\ r = 1,2,\dots,n;\ i = 1,2,\dots,n \quad (24)$$

The transition matrix showing bus delays at traffic light objects on a route section is expressed by a square matrix with size n. Along the diagonal of the matrix the probabilities ($p_{ii}(r)$) of remaining in a state S_i at a step r are shown, along the other cells the probability of transition ($p_{ij}(r)$) from state S_i to state S_j. The sum of the probabilities across all rows of the matrix will be equal to 1:

$$\sum_{j=1}^{n} p_{ij}(t) = 1 \quad (25)$$

Based on the initial unconditional matrices, other unconditional matrices are determined for the system to be in the situation S_i as follows:

$$p_j(r) = \sum_{i=1}^{n} p_i(r-1)p_{ij}, \quad r = 1,2,\ldots,n,\ j = 1,2,\ldots,n \qquad (26)$$

Прибытие автобусов на все остановки по маршруту The arrival of buses at all stops along the route obeys Poisson's law, and this happens with intensity λ_{ij} over a certain time t. The desired probabilities (time functions) of the Markov chain $p_i(t)$ show that the system is in a state S_i at the moment t, and we find them from the Kolmogorov system of differential equations. In matrix form, the equation can be written as follows:

$$\frac{dP(i,t)}{dt} = P(i,t) \cdot L \qquad (27)$$

Where L is the speed vector of the Poisson flow. The initial conditions for equation (27) will be as follows:

$$t = 0;\ p_1(t) = 1;\ p_2(t) = p_3(t) = \ldots = p_n(t) = 0 \qquad (28)$$

When solving a system of equations, the normalization condition is accepted:

$$\sum_{j=1}^{n} p_i(t) = 1 \qquad (29\ )$$

The number of bus stops at 4 consecutive traffic light objects on Rashid Behbudov Street in Baku was determined based on live observations. Figure 10 shows a diagram showing delays and bus crossings for a section of the route with four signalized intersections.

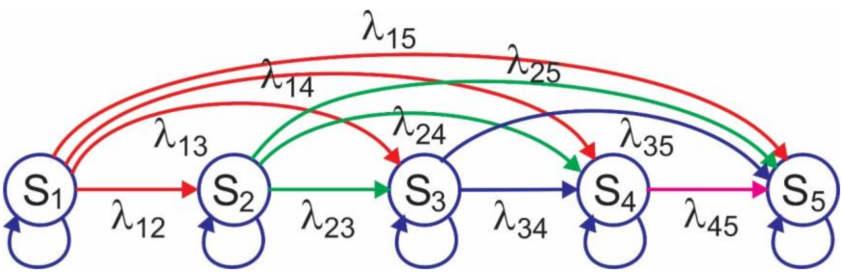


Figure 10. Delay process graph

S1 - shows the passage of buses along a section of the route without hitting a traffic light, and *S2, S3, S3, S4* - shows the delay at the 1st, 2nd, 3rd and 4th traffic lights, respectively. As you can see, the delay of a bus at an intersection on a section of the route is a discrete Markov process, continuous in time. Let's create Kolmogorov's equations for this model:

$$\begin{cases} \dfrac{dp_1(t)}{dt} = -p_1(t)(\lambda_{12} + \lambda_{13} + \lambda_{14} + \lambda_{15}) \\ \dfrac{dp_2(t)}{dt} == -p_2(t)(\lambda_{23} + \lambda_{24} + \lambda_{25}) + p_1(t)\lambda_{12} \\ \dfrac{dp_3(t)}{dt} == -p_3(t)(\lambda_{34} + \lambda_{35}) + p_1(t)\lambda_{13} + p_2(t)\lambda_{23} \\ \dfrac{dp_4(t)}{dt} == -p_4(t)\lambda_{45} + p_1(t)\lambda_{14} + p_2(t)\lambda_{24} + p_3(t)\lambda_{34} \\ \dfrac{dp_5(t)}{dt} == p_1(t)\lambda_{15} + p_2(t)\lambda_{25} + p_3(t)\lambda_{35} + p_4(t)\lambda_{45} \end{cases} \quad (30)$$

or

$$\frac{dp_i(t)}{dt} = \begin{bmatrix} -p_1\lambda_{12} & -p_1\lambda_{13} & -p_1\lambda_{14} & -p_1\lambda_{15} \\ -p_2\lambda_{23} & -p_2\lambda_{24} & -p_2\lambda_{25} & p_1\lambda_{12} \\ -p_3\lambda_{34} & -p_3\lambda_{35} & p_1\lambda_{13} & p_2\lambda_{23} \\ -p_4\lambda_{45} & p_1\lambda_{14} & p_2\lambda_{24} & p_3\lambda_{34} \\ p_1\lambda_{15} & p_2\lambda_{25} & p_3\lambda_{35} & p_4\lambda_{45} \end{bmatrix} \quad (31)$$

By solving equation (31), we can estimate the limiting values of the probability of bus stops at traffic light objects for a real section of the route. Normalization condition:

$$p_1 + p_2 + p_3 + p_4 + p_5 = 1 \quad (32)$$

In general, if there are 4 traffic light objects on a route section, the average bus delay time in the route area can be determined as follows based on certain boundary probabilities:

$$t_{len} = \frac{t_{q1}}{2} p_1 + \frac{t_{q2}}{2} p_2 + \frac{t_{q3}}{2} p_3 + \frac{t_{q4}}{2} p_4 \quad (33)$$

Where t_{qi} – duration of the prohibiting signal at the traffic light object number i, sec.

As a result of solving the system of equations, the probability of buses traveling without stopping along a section of the route depending on the number of traffic light objects (m = 1,2,3,4) is graphically presented in Figure 11.

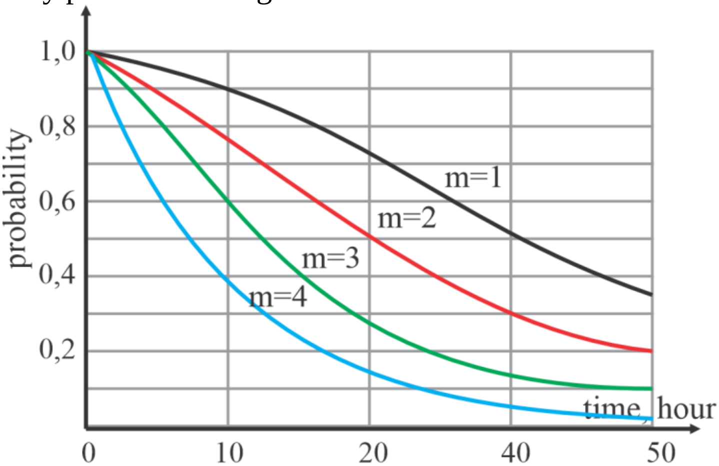


Figure 11. Probability of buses traveling along a section of the route without delay depending on the number of traffic light objects

Based on the proposed methodology, it is possible to estimate the average delay time at each intersection, describing cases of delay at traffic light objects along a route section as a Markov process.

The fifth chapter of the dissertation is devoted to the organization of the functioning of buses at route stops, the use of methods for assessing the capacity of stops, the creation of a simple analytical model for coordinating bus routes at stops, and the construction of a simulation model of the operation of intensively used bus stops.

As a result of research conducted in the USA, the following formula was proposed to determine the capacity of a bus stop[6]:

[6] Highway Capacity Manual 2000. / Transportation Research Board, National Research Council. - Washington, D.C., USA, - 2000, - 1134 p.

$$B_S = N_{eb} B_{bb} = N_{eb} \frac{3600 \cdot \frac{g}{C}}{t_c + \frac{g}{C} \cdot t_d + z_a \cdot c_v \cdot t_d} \quad (34)$$

Where N_{eb} is the number of places designated for buses at stop; B_{bb} is the launch capacity of one stop point; g lighting period of green light; C length of settlement cycle of traffic lights; t_c time when the bus leaves the stop; t_d time during which bus is at the stop; z_a supposition on the increase of queues before the stop; c_v variations of incoming intervals.

We observe that the values of the quantity t_d change over a wide range at stopping points in different areas of the city of Baku. This is actually due to the variety of vehicles and quality of service.

If there is no controlled intersection or traffic light after a stop, the capacity of the stop is determined as follows:

$$B_S = N_{eb} B_{bb} = N_{eb} \frac{3600}{t_c + t_d + z_a \cdot c_v \cdot t_d} \quad (35)$$

The calculations use the values of t_c, determined by theoretical studies.

The results of measurements carried out at 5 bus stops in Baku show that the time a bus spends at a stop (t_d) varies from 8 to 232 seconds.

As a result of the high traffic intensity of shuttle buses, queues at bus stops appear on some streets of Baku. If a large number of buses of different routes arrive at a stop at different intervals, the problem can be solved by grouping bus routes by their intervals and coordinating them with each other. To simplify the solution of the problem, it is convenient to first consider a group with a large number of routes. Let's assume that the number of routes included in group III is greater than others. To begin with, let’s take the travel intervals of routes in this group to be equal to i_{III} (min). If route buses move at a given interval n_{III}, then schedules should be drawn up to ensure the arrival of their buses from the stop in front of the section in question with a difference $\dot{I}_{III}/n_{III}$. In this case, the probability of simultaneous arrival of buses on the route in question at stops in the matching zone will be very low. The generally accepted interval should be determined in such a way that it is completely divisible by the number of routes that will work with this interval ($\dot{I}_{III}/n_{III} \in N$). If this is not possible, it is necessary to change the composition of the groups and increase the number of groups. At the next stage, the schedules of other groups are adjusted in a similar way and the simultaneous arrival of buses of the routes of these groups at the stop is prevented. If the routes of the two groups under consideration have a common denominator of traffic intervals, then it is possible to coordinate the work of these two groups and ensure that the buses of these groups arrive at the stop at different times (Figure 12).

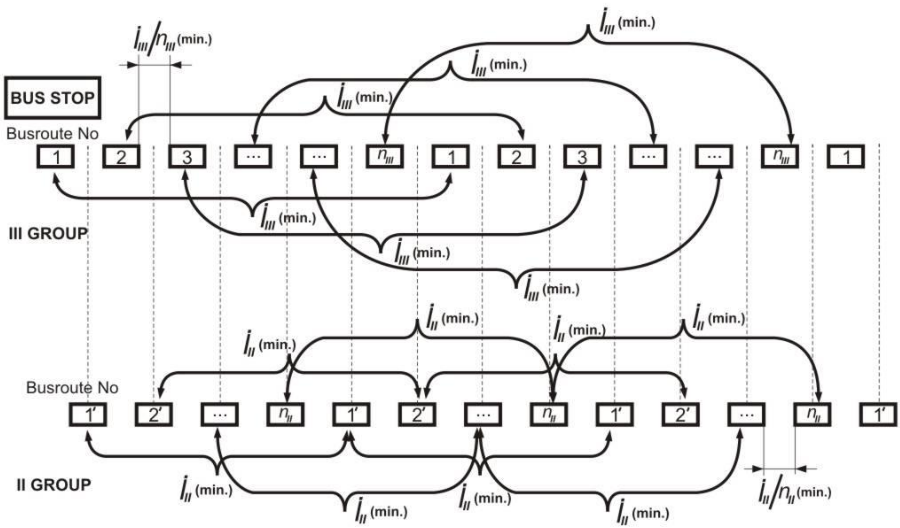


Figure 12. Scheme for coordinating the work of bus groups at different intervals (Option I)

The ideal case can be presented as in Figure 13. As a result of applying this model, buses of only separate groups of routes simultaneously arrive at stops in the area under consideration. And so the maximum number of buses simultaneously arriving at a stop will correspond to the maximum number of organized groups.

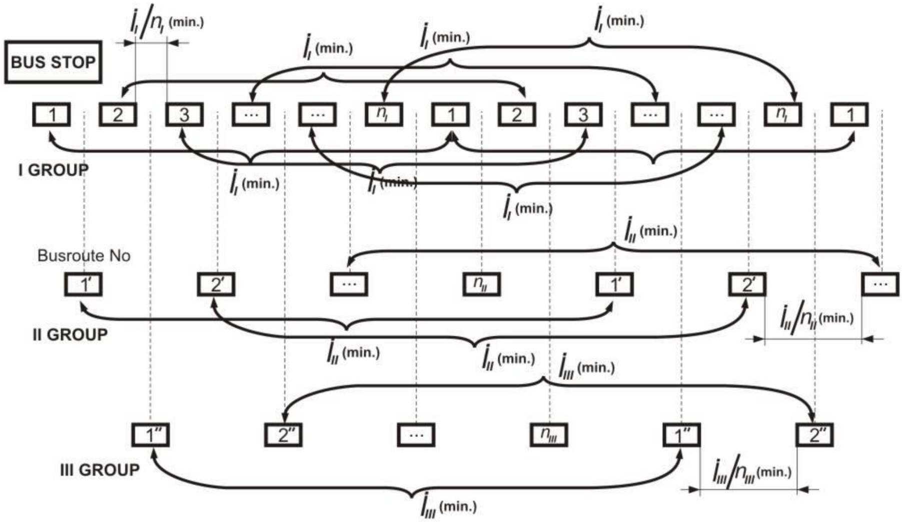


Figure 13. Scheme for coordinating the work of bus groups at different intervals (Option II)

If the number of groups of routes passing through a stop is large with such a coordinated organization of route work, the implementation of the scheme becomes too complex. Therefore, there is a need to create a mathematical model of a precisely calculated sequence of bus arrivals at a stop and check it using computer simulation models.

There are 3 main types of computer simulation: system dynamics; discrete event modeling and agent-based modeling. Of these, agent-based modeling is the most suitable for modeling bus route networks.

A simulation model of a bus route is created using the ***CarSource, CarMovie to, CarDispose, BusStop, Delay*** tools of the ***Road*** library in various versions of the ***Anylogic*** program. One of the main advantages of the program is the ability to enter in advance bus intervals, the number of buses, the number and location of stops, just like on a real bus route. The logical diagram of a bus route simulation model can be constructed as in Figure 14.

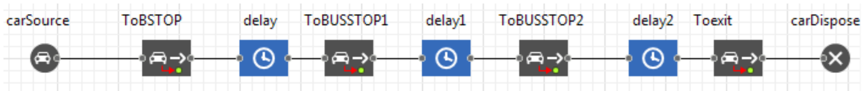
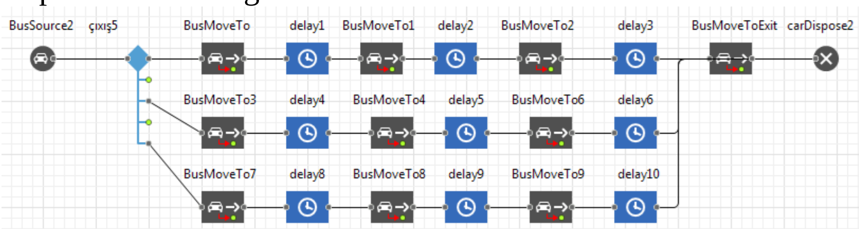


Figure 14. Logical diagram for constructing a bus route

The nature of changes in the number of passengers arriving at a departure point can be studied in a simulation model using the ***Pedestrian*** library.

An example of a logic diagram for bus departures from one initial stop is shown in Figure 15.



Rice. 15. Construction of an algorithm for modeling routes starting from one initial stop

The logical diagram of the simulation model of routes with coinciding stops is presented in Figure 16. The parameters for waiting for a bus at a stop are entered using the ***Delay*** tool.

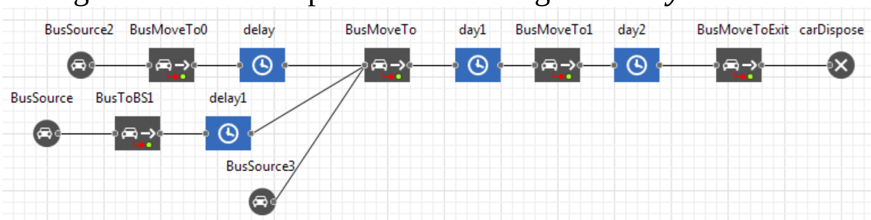


Figure 16. Construction of an algorithm for modeling routes with coinciding stops

You can take into account the regularity of passengers arriving at a stop using the ***PedSource*** tool. We know that in any considered time interval t, the number of passengers m arriving at a stop during normal hours is distributed according to Poisson's law with the parameter λt:

$$P_m(t) = \frac{e^{-\lambda t}(\lambda t)^m}{m!} \qquad (36)$$

Where λ the average intensity of passenger arrivals at the stop. For two consecutive bus stops (initial and next), the logical model for passengers entering and exiting the bus will be in Figure 17.

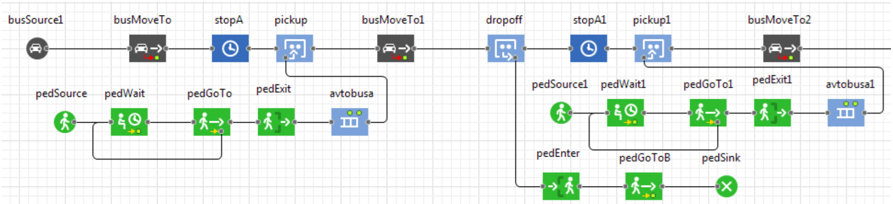


Figure 17. Pattern of passenger boarding and alighting at two consecutive stops.

Using software, you can create various scenarios, as well as monitor the movement of buses along the route in various conditions, entering the operating modes of traffic lights, the number of lanes, traffic intensity on the road.

Bus stops with the highest congestion and queues in Baku are a stop near the “8th km” market, stops near the Neftyaniki and Gara Garayev metro stations and a stop located on Moscow Avenue (Table 7). Depending on the time of day and bus schedule, the number of buses arriving at the stop in front of the 8th km market varies from 145 to 180 units per hour. At this stop, density is observed from 7 am to 8 pm.

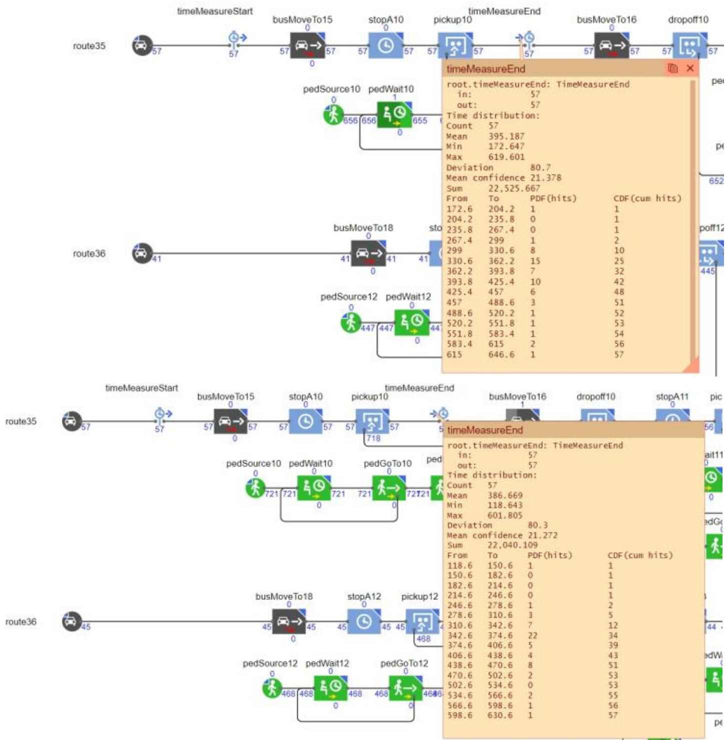
Table 7. Indicators of bus routes at intensively used stops

Stop	The number of routes passing through the bus stop
8th km Bazaar	11,12,15,22,35,36,40,44,49,50,51,54,57,60,62,64,70,7a,81,
Shamakhinka	2,13,14,18,29,37,65,67,7a,83,92,119, 135,156,170,193,199,525
metro station Neftchilar	11,12,15,22,35,36,40,44,49,50,51,54,57,60,62,64,70,7a,81
Metro station 20 January	2,13,14,18,29,37,65,7a,83,102,119,159,193,199, 114a,114b

We are considering a stop near the “8th km” market, which is one of the busiest in Baku.

When analyzing the situation at the stop, introducing the arrival of buses at the stop by interval, hourly intensity and traffic schedule used in existing conditions, it was revealed that the queues of buses in front of the stops are of a different nature. The arrival of buses by interval and based on a certain pattern (normal distribution) is entered using İnterarrival time, and their arrival frequency is entered using the Rate parameter.

When you enter the arrival of buses at the stop of route No. 35 according to the interval in the existing version (Figure 18, a) and the number of buses per hour (frequency) of movement (Figure 18, b), the time elapsed from the moment the buses appear in the model until leaving the stop changes abruptly, and the distribution of this change has a different character.



a)

b)

Figure 18. Results of measurements of the time it takes to pass a stop by buses on route No. 35

Figure 19 shows graphs of the distribution of time lost to travel through a stop when buses arrive at a stop according to the interval and hourly frequency on route No. 35.

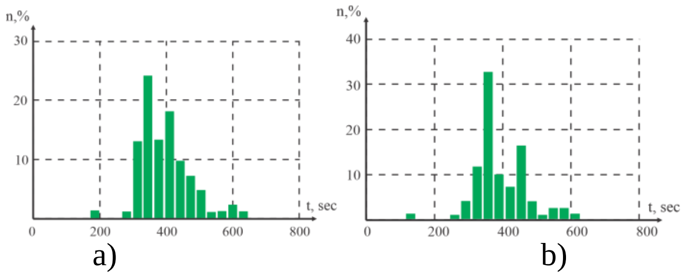


Figure 19. Distribution of time losses when buses arrive at a stop by interval (a) and arrival frequency (b) for route 35

The proposed bus route simulation model can be applied to stops of other types of street public transport and mixed-use stops with equal efficiency.

The sixth chapter is devoted to the analysis of the operation of buses of different routes at stops with high traffic density, the time spent at the stop, as well as the development of a method for reducing time loss at stops with modeling the order of arrival of buses at the stop while observing traffic intervals.

As already mentioned, one of the most heavily used bus stops in Baku is the stop in front of the 8th Kilometer market. As can be seen from the schematic image of the “8th km bazaar” stop based on a satellite image (Figure 20), there is a traffic jam at the stop and queues of buses entering the stop.

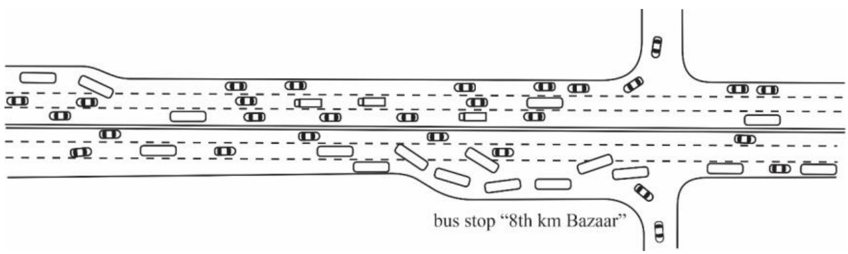


Figure. 20. Schematic representation of the stop “Market 8th km” based on a satellite image (from Google Earth)

If a vehicle stop uses a large number of routes, there is a need to coordinate the operation of these routes, and modeling the order of arrival of buses can reduce time losses by ensuring high accuracy of movement.

The regularity of movements is calculated to evaluate the performance of all considered rides. Punctuality is the arrival of buses at each stop at the scheduled time. The accuracy index of buses can be determined as follows:

$$P = \frac{s^2}{h_t^2} \tag{37}$$

Where h_t scheduled interval, s^2 is calculated as follows:

$$s^2 = \frac{\sum_{i=1}^{I}(t_i - \tau_i)}{I} \tag{38}$$

Where t_i real time of arrival of the i-th bus at the stop, τ_i time of arrival of the *i*-th bus at the scheduled stop, I number of arrivals at the stop.

The number of buses passing through a stop j per hour along a route i can be calculated as follows:

$$A_{ij} = \frac{60}{\dot{I}_i} \tag{39}$$

Where $\dot{I}_i$ - Route interval i, min.

If buses on routes passing through a stop arrive at the stop at regular intervals, then the number of buses arriving at the stop j in one minute can be found as follows:

$$A_{j,1deq} = \frac{\sum_{i=1}^{n} A_{ij}}{60} = \frac{\sum_{i=1}^{n} \frac{60}{I_i}}{60} = \sum_{i=1}^{n} \frac{1}{I_i} \tag{40}$$

Where $i = 1...n$ number of routes passing through the stop.

In order to reduce queues before the stop and reduce delays due to the business of the stop, we adjust the time of arrival at the parking lot, maintaining the values of traffic intervals on routes in accordance with those calculated according to passenger flow. For this purpose, we simulate the arrival time of buses at the stop, as shown in Figure 21, shifting the arrival time of buses at the stop in the schedules and limiting the number of buses arriving per minute to 6.

The time of arrival at the considered stop is planned in order from the route with the smallest interval of movement to the route with the largest interval. r shows the bus route, i interval in the route, t minutes of arrival of the bus at the stop during hours. When the value of A is 1, it means that the bus will arrive at the stop at the given minute, and when it is 0, it means that it will not arrive. For example, $A_{r1;t(1+ki_1)} = 1$, $(k = 0,1,2..n)$ means that buses of route r_1 arrive at the stop on the 1, $1+i_1$, $1+2i_1$ etc. minutes.

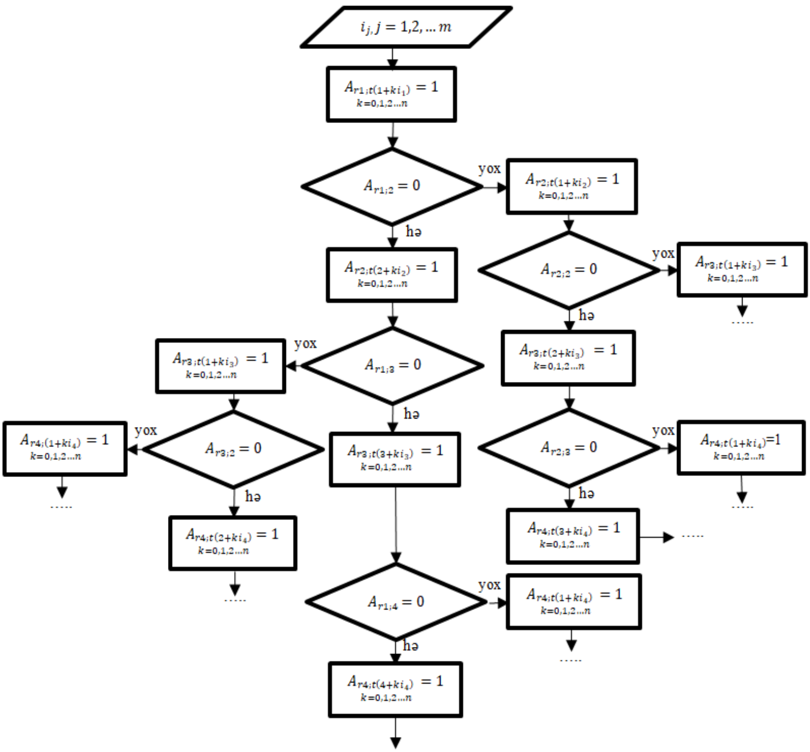


Figure 21. Model for determining the time of arrival of buses at a stop

Based on the proposed arrival model, the order of arrival of buses along the routes will be as in Table 8.

Table 8. The order of arrival of buses at stops along routes in accordance with the actual traffic interval

Routes	Minutes of the hour																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
50	1	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0
62	0	1	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	1	0	0
64	0	0	1	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	1	0
81	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	1
12	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0
51	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0
49	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0
40	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
57	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
11	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
15	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0
60	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0
7a	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0
44	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
35	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
36	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0
70	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
22	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
54	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
N_{bus}	4	4	4	3	3	3	3	3	2	4	5	2	3	3	3	5	4	3	1	1

As can be seen from Table 12, the number of buses arriving at a stop (***N_{bus}***) with the proposed sequence will not exceed 5 in any given minute.

We use the ***Schedule*** parameter of the program to enter the time of arrival of buses at the stop in accordance with existing traffic intervals according to the proposed times of arrival of buses at the stop.

Due to the comparison of time losses caused by queues when buses approach a stop using the existing and proposed options, in the calculations the stop time is taken to be constant (30 seconds) in both cases. In real conditions, the intensity of traffic flow is 1000 vehicles/h, and the speed limit is 50 km/h. In accordance with existing conditions, the number of stopping places at the bus stop is 3, the length of the stop is 55 meters, and the length of the bus itself is 12 meters.

Figure 22 shows comparative values of the minimum and maximum time required to pass a stop, after entering other stop parameters and bus routes. recorded as a result of the simulation experiment for the first 3 hours.

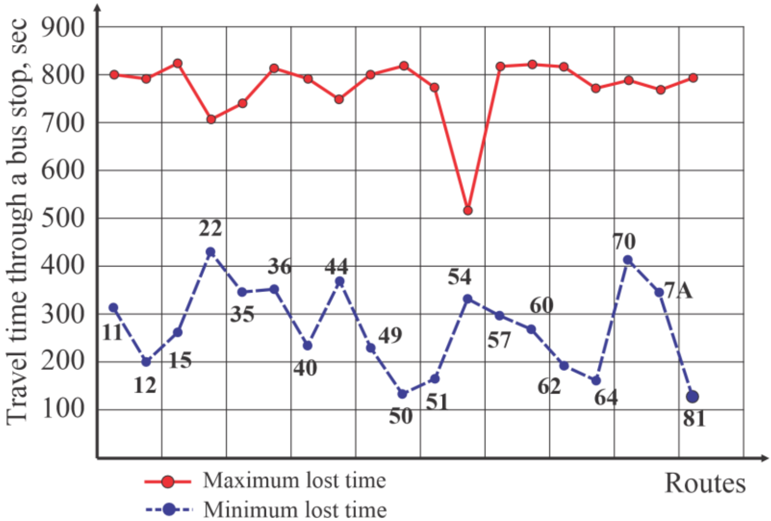


Figure 22. Minimum and maximum values obtained as a result of testing the passage of buses along routes, through a stop for 3 hours

As a result of coordinating the arrival of buses at the stop, as well as the introduction of special lanes for buses, the average travel time of buses from the stop is seriously reduced. Application of the proposed model of bus arrival at a parking lot reduces the time a bus passes through a stop by an average of 114.24 seconds. This reduction is 130.26 seconds when using a dedicated bus lane for both bus arrival scheduling scenarios.

Figure 23 shows the distribution of time for a bus to pass a stop for cases of arrival at a stop in accordance with the existing traffic interval and in accordance with the proposed coordination model when moving in the general flow and after using a special lane.

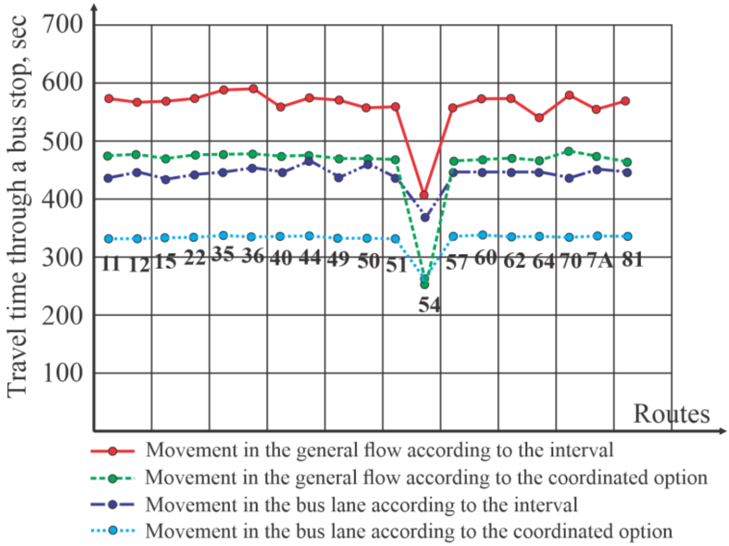


Figure 23. Distribution of time for buses to pass a stop in the general flow and on a specialized lane

Even when using a bus lane, as the period under study increases, the time it takes for buses to pass a stop, and for buses to arrive at the stop in accordance with the prescribed interval, increases with a very large jump. However, under the same conditions, i.e., with the same number of bus stops, when using a bus lane and a model for coordinating the arrival of buses at a stop, the transit time at the stop is significantly reduced.

Thus, the proposed form of organizing the arrival of buses at a stop is effective both when buses move in the general flow and when using a special lane.

The seventh chapter of the dissertation is devoted to the development of a methodology for assessing the efficiency of the bus route network, assessing the possible economic effect of reducing temporary losses of buses and passengers as a result of applying the proposed model for queuing the arrival of buses at stops with high traffic density.

The efficiency of links in a bus route network is proposed to be determined as the ratio of the number of passengers transported along these links in a certain time to the time of crossing this link. In this case, the efficiency indicator for sections of the route network will be calculated as follows:

$$Ef_l = \frac{Q_l}{t_l} \tag{41}$$

Where Q_l the number of passengers transported on the section (passenger flow), t_l time of passage of the section p. Latora and Marchori propose the following expression to evaluate the efficiency of the overall transport network:

$$Ef(G) = \frac{1}{N(N-1)} \sum_{i \neq j \in G} \frac{1}{d_{ij}} \tag{42}$$

Where N the number of links in the network, d_{ij} the shortest distance between the vertices i and j.

When determining the efficiency of a bus route network, it is important to consider the number of passengers carried. Therefore, we propose the following formula for determining the efficiency of the bus route network:

$$Ef(G) = \frac{1}{N(N-1)} \sum_{i \neq j \in G} \frac{Q_{ij}}{t_{ij}} \tag{43}$$

The nature of the change in the travel time of a road section with different traffic intensity on the section of the Baku route network based on the previously proposed 3 models is shown in Figure 24.

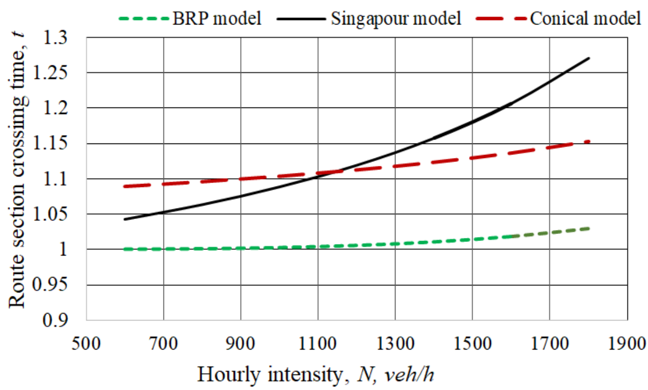


Figure 24. Change in travel time of a route network section when using different models

Based on the results of live observations on the section of the route network under consideration, the nature of the distribution of time losses of buses on the section depending on the hourly traffic intensity is shown in Figure 25.

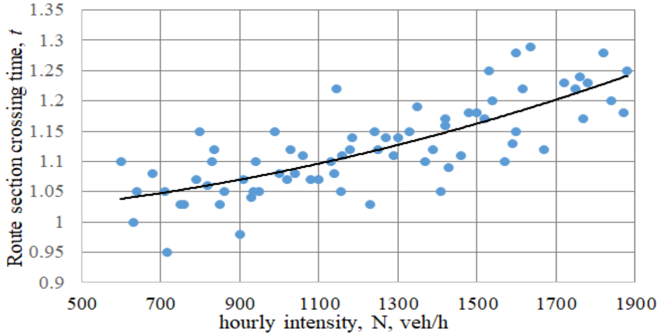


Figure 25. Change in travel time of a section of the road network in real conditions depending on the intensity of traffic flow

The nature of the trend curve in Figure 25 and the values on it correspond with sufficient accuracy to the nature and values of the curve obtained when applying the Singapore model to determine time losses.

Then the formula for assessing the efficiency of the urban route network can be written as follows:

$$Ef(G) = \frac{1}{N(N-1)} \sum_{i \neq j \in G} \frac{Q_{ij}}{\frac{l_{ij}}{V_{ij}^{0}} + 0{,}9\left[\frac{C(1-\lambda)^2}{2(1-\lambda x_{ij})} + \frac{x_{ij}^2}{2N_{ij}(1-x_{ij})}\right]} \qquad (44)$$

Daily values of time lost during the organization of the transport process are determined as follows[7]:

$$Q_{gvi} = \sum_{i} T_l Q_v Z N \qquad (45)$$

Where T_l daily lost time, Q_v price per unit of time losses, man, Z degree of occupation, N number of passed vehicles.

[7] Bivina, G.R. Socio Economic Valuation of Traffic Delays / G.R.Bivina, L,Vishrut, K.V.S Sanjay // Transportation Research Procedia, - 2016, 17, - p. 513-520

Based on formula (45), it is advisable to determine the savings in time lost for bus travel through the stop zone under consideration using the following formula:

$$Q_{gvi} = \frac{T_{qi}}{3600} \frac{D_i}{t_{pi}} A_i Q_{vi} 365 \tag{46}$$

Where T_{qi} time savings from applying the proposed coordinated arrival time of one bus for the period under consideration, seconds, D_i daily operating hours on the route, hour, A_i the number of buses traveling during the period under review, t_{pi} the duration of the period under review, hour, Q_v cost of a unit of time loss, manat. For buses, a portion of the daily profit is accepted, passing by an hour, and on average in the city of Baku you can take 10 manats.

According to the proposed model of coordinated arrival of buses at the stop in question, when buses move in the general flow, the benefit received from saving time during the year will be 381045 manats, when moving along a special lane, it will be 446285 manats.

Based on the number of buses arriving at the stop during the period under review, the annual economic effect from reducing the time spent passing the stop, obtained as a result of the simulation experiment, will be 379974 manats when buses move in the general flow and 450572 manats when moving in a special lane.

The cost of additional passenger waiting time can be estimated based on the waiting time, the fixed cost per hour and the number of passengers [8]:

$$X_{üm} = \frac{t_{göz} Q S_n}{60} \tag{47}$$

Where $t_{göz}$ average waiting time for passengers, seconds, Q number of passengers transported, people, S_n norms of revenue per

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[8] Бычков В. П. Управление системой городского пассажирского транспорта: монография / В. П. Бычков, Г. В. Шипилов : Фед. агентство по образованию, ГОУ ВПО «ВГЛТА», Воронеж, 2009. - 155 с.

hour of work, man. The price of one standard hour can be taken as 2 manats according to the average earnings of workers.

Taking into account formulas 46 and 47, the annual savings from reducing the loss of passenger time as a result of reducing bus delays at the stop can be calculated as follows:

$$X_{üm-sern} = \frac{t_{göz} A q \gamma S_n}{3600} \frac{D_i}{t_{pi}} 365 \qquad (48)$$

Where q nominal capacity of the bus, passenger, γ bus fill factor (average daily value for bus routes passing through the stop in question $\gamma = 0{,}4$).

As a result of applying the proposed model of the time of arrival of buses at a stop, the annual economic effect from saving time lost by passengers will be 2333892 manats when buses move in the general traffic flow and 2735286 manats when buses move along a special lane.

Using the proposed model for the arrival of buses at a stop, the total annual economic effect as a result of reducing the delay time of buses and passengers at the stop in question when buses move in the general flow will be 2714937 manats, and when moving along a special lane, 3181571 manats.

RESULTS AND PRACTICAL RECOMMENDATIONS

1. The main requirements of the logistics approach to urban public transport, including city bus transport, is the provision of high-quality transport services to passengers. To maintain the quality of passenger service at a high level, it is important to study the attitude and demand of passengers towards the operation of the city bus route network [7,9].

2. Among the numerous indicators that determine the quality of urban public transport, passengers are more interested in safety, delivery times and ride comfort. In surveys conducted in the city of Baku in 2022, the majority of respondents consider it advisable to create a network of alternative types of public transport. Creating a network of a new type of transport will require a reassessment of the demand for routes and vehicles of other types of public transport [17].

3. The creation of a system of high-speed bus routes is very effective as an alternative to bus transportation in cities, its creation does not require large funds, and there are favorable conditions for its creation on several main streets of Baku [11].

4. To ensure the quality of service in the bus route network, a method for selecting rolling stock using multi-criteria decision-making methods (MAP and TOPSIS) in accordance with the needs of passengers is proposed, and this technique can be used when selecting buses on urban and suburban routes [15].

5. Based on the values of the time loss of vehicles passing through the parking zone with various forms of organizing stops, obtained in tests carried out with the proposed simulation model, it was established that the delays of buses when organizing a stop near the curb takes on large values. This delay is more pronounced when there are few lanes. Increasing the frequency of bus arrivals at stops organized in a “pocket” increases delays in traffic flow. However, an increase in the intensity of traffic flow does not have a serious impact on this growth [21].

6. An analysis of the influence of various factors on the speed and travel time of buses on sections of city routes was carried out. The

results of the analysis show that with constant values of the influencing factors, the travel time of the bus along sections of the route varies within wide limits only due to the influence of the vehicle and driver factors [2].

7. In order to reduce delivery time, which is one of the main quality indicators in public transport, a mathematical model has been developed for estimating and predicting random delays on route sections. Considering that delays on bus routes depend on the operating modes of traffic lights, it is proposed to consider this process as a discrete Markov process continuous in time. The proposed methodology can be used to estimate time losses when scheduling buses [22,23,24].

8. To reduce the loss of time of buses at stops on bus routes with coinciding stops, an analytical method for grouping routes by travel intervals and sequence of arrival time at the stop is proposed [4]. A methodology for creating a simulation model of a bus route network has been developed. This technique makes it possible to identify real obstacles that cause delays in the movement of buses when they travel along the entire network or along sections of roads with different traffic conditions [12,13,14,18].

9. A mathematical iterative model of the sequence of bus arrivals at stops used by a large number of bus routes has been proposed, and simulation tests have shown the effectiveness of the proposed model [20].

10. A methodology has been developed for assessing the efficiency of route network links based on calculating the number of passengers passing through a link per unit of time, the use of which makes it possible to better reflect the actual traffic conditions on the route [19].

11.The use of a coordinated queue of bus arrivals at intensively used stops on the route network is also cost-effective.

The main points of the dissertation are presented in the following articles:

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2.Dashdamirov, F. Study of bus driving parameters on urban route // Transport problems, - 2011, 6(4), - p. 79-85.

3.Daşdəmirov, F.S. Nəqliyyat axınının sürətinin avtobusların xəttə işinə təsiri // "Heydər Əliyev və Azərbaycan təhsili" mövzusunda Respublika Elmi konfransı, AzTU, Bakı, - 07-08 may. 2013, - s. 299-301.

4.Dashdamirov, F. Coordination of the work of buses in city routes // Transport Problems, International scientific journal. ISSN 1896-0596. The Silesian University of Texnology, - 2013, 8(4), - p. 77-82

5.Daşdəmirov, F.S. Dayanacaqları üst-üstə düşən marşrutlarda avtobusların işinin təşkili // Nəzəri və Tətbiqi Mexanika, - 2015, №4, - s. 58-62.

6.Daşdəmirov, F.S. İctimai nəqliyyatın dayanacağının buraxma qabiliyyətinə təsir edən amillər // AzTU-nun elmi əsərləri, Bakı, - 2015. №4, - s.120-123.

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12.Daşdəmirov, F.S. Anylogic mühitində marşrut şəbəkəsinin imitasiya modelləşdirilməsi // Peşə təhsili və insan kapitalı, - 2020, 3(2), - s. 73-77.
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