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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

CAUSES OF TRAFFIC CONGESTION IN CITIES AND THEIR ELIMINATION

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GENERAL CHARACTERİSTİCS OF THE WORK

Relevance of the study and Degree of Development. The rapid growth of motorization has led to issues such as people being stuck in "traffic congestion", time losses, disruption of the ecological balance, the emergence of nervousness and stress, an increase in the number of road traffic accidents, and other related problems.

In the Republic of Azerbaijan, in 2023, the share of road transport in passenger transportation in the transport sector was 88.1%, while the share of other modes of transport was metro 11.4%, railway 0.37%, air 0.15%, and sea 0.001%. The share of road transport in passenger turnover was 75.8%, while the shares of other modes of transport were air 15.6%, metro 7.7%, railway 0.93%, and sea 0.03%. Statistical indicators show that road transport has a significant advantage in transportation in the Republic of Azerbaijan.

In addition, in a number of leading countries around the world, Intelligent Transport Systems (ITS) have been built and put into operation, simulation programs (such as VISSIM, VISUM, AIMSUN, etc.) have been implemented for the purpose of forecasting traffic flows, and smart city and other projects have been carried out.

One of the main components of an Intelligent Transport System is the traffic signal control section, where a key element of its operation is the adaptive installation of a coordinated regulation schedule (the "Green Wave" mode).

Considering the above, it can be confirmed that a dissertation focused on the causes of traffic congestion in cities and their elimination is highly relevant in terms of the current demands.

Research Object and Subject. The research object of the dissertation is traffic congestion, transportation density in cities, while its subject is preventing these issues and improving transportation conditions. Based on the results of the research, it is emphasized that determining the average speed of vehicles is an important indicator in assessing road density, as well as in the adaptive adjustment of the "Green Wave" mode.

For this purpose, while investigating the causes of traffic congestion in cities and their elimination, a number of scientific works and articles by various authors have been used and referenced in the course of the research on the current topic.

Aims and Objectives of the Research. The goal of the research is to reduce traffic congestion in cities and establish the "Green Wave" mode by using new approaches in the field of transportation management.

In line with the chosen goal, the following issues are to be addressed:

- Investigating the causes of traffic congestion in Baku city;
- Forecasting traffic speed on city streets and roads based on the concept of smart mobility;
- Investigating the application of a neural network model and artificial intelligence for reliable forecasting of transportation flow parameters;
- Regulating traffic flow in the northern entrance-exit direction of Baku city and promoting the use of public transport by passengers;
- Implementing the obtained approaches and results on a number of streets and roads in Baku;
- Calculating the economic efficiency gained from reducing traffic congestion and decreasing environmental pollution in Baku city using the proposed approach..

Research Methods. To achieve the goal set in the dissertation, data obtained from the Traffic Intelligent Management Center (TIMC) video vehicle detection system (VVDS) and controllers, as well as statistical processing of the data, application of neural networks, and simulation methods were used.

Based on the conducted studies, the research was continued in the following areas:

- Application of innovative approaches;
- Construction of a neural network;
- Expansion of public transportation;
- Improvement of road infrastructure.

Key points presented for defense:

- Investigating and forecasting the velocity of motor vehicles as a complex indicator of traffic flow;

- Creating training, evaluation, and test datasets for forecasting the velocity of motor vehicles;
- Developing smart projects aimed at increasing the efficiency and safety of traffic organization;
- Forecasting traffic performance indicators using artificial intelligence capabilities;
- Developing a "Green Wave" mode project using neural network applications on Matbuat Avenue and Academic Zarifa Aliyeva Street in Baku;
- Developing a method for evaluating the results of neural network training.

Scientific Innovation of the Research.

- A method has been developed to ensure the safety of pedestrian and vehicle movement around service facilities, where there is a high density of pedestrians and vehicles, in order to reduce traffic congestion at the city entrances and exits.
- Neural networks have been established for the adaptive organization of the "Green Wave" mode.
- Data regarding the velocities of motor vehicles at real urban street intersections and from surveillance cameras have been analyzed to create test datasets for the model developed through the neural network;
- The work of technical traffic regulation tools and all factors influencing traffic organization, such as movement intensities and velocities, has been studied on the selected streets and avenues, and the velocity, used as an input parameter, has been predicted with 95% accuracy.

Theoretical and Practical Significance of the Research. The main results obtained have significant theoretical and practical importance. The development of road transportation in the modern era impacts various aspects of the economy, culture, and social life. This development has both positive and negative aspects, with its speed now encompassing not only economic but also social issues. Furthermore, in the practical phase, road transport development raises issues such as traffic congestion, time loss, environmental problems, increased nervousness and stress, and a rise in transportation accidents. The theoretical foundation of the dissertation is based on numerous studies, scientific research, references to works by both local and foreign authors, as well as participation in various conferences related to the topic.

Approval and Implementation. The main points of the dissertation have been presented and discussed at various scientific conferences, including the following: the Republican Scientific Conference on "Globalization and Regional Integration" organized by the Ministry of Education of the Republic of Azerbaijan at Mingachevir State University (Mingachevir, 2016), the XX Republican Scientific Conference of Doctoral Students and Young Researchers (Baku, 2016); the Republican Scientific-Technical Conference dedicated to the 94th anniversary of the birth of the national leader of the Azerbaijani people, Heydar Aliyev, held at Azerbaijan Technical University on the topic of “Youth and Scientific Innovations” (Baku, 2017); the International Scientific-Practical Conference on "Azerbaijan in the International Transport System: Goals and Perspectives" at Baku Engineering University (Baku, 2018); the Republican Scientific Conference on "Transport of Azerbaijan: Achievements, Problems, and Perspectives" (Baku, 2019); and the II International Scientific-Practical Conference on "Progressive Research in the Modern World" (Boston, 2002).

The findings of the dissertation have been further explored through participation in various local and international training programs aimed at mastering modern methods and techniques. These include the following: the “International Road Safety Engineering” seminar held in Baku in 2019, the “Infrastructure Planning and Development” seminar held in Beijing, China in 2019, the “Bus Transport Systems Planning” training program held in India in 2020, the "EBRD – Road Safety Engineering" Webinar in 2021, the "Development of Road Safety Engineering" Seminar for CAREC countries (Kazakhstan) in 2021, the Asia-Pacific Safe Road Infrastructure Webinar in 2022, the "Development of Road Safety Engineering" Seminar for CAREC countries (Turkmenistan) in 2022, the International Regional Road Safety Research Dialogue and the Asia-Pacific Road Safety Research Annual Meeting held in the

Philippines in 2022, the "Evaluation of Arterial Signal Coordination Performance Using Automated Vehicle Trajectories" training in Florida and obtained certificates for these programs.

Furthermore, a patent for the "Method of Ensuring the Safety of Pedestrian and Vehicle Movement in the Bus Station Area" was granted by the Intellectual Property Agency of the Republic of Azerbaijan under the patent number I2020 0041.

The main provisions of the dissertation have been implemented in the ITMC, the authorized institution responsible for traffic light management in Baku. A report was prepared regarding the proposed method for eliminating traffic congestion, which includes the possibility of adaptively changing the “Green Wave” mode at any time of the day. The implementation of this method is expected to help reduce delays in traffic flow.

Considering the practical significance of the "Green Wave" mode outlined in the dissertation, the "Signal" Specialized Project Production Department of the Main State Traffic Police Department of the Ministry of Internal Affairs, which is responsible for traffic light management in other cities and regions of the Republic of Azerbaijan, has adopted the proposed measures. Based on the findings of the dissertation, an act was prepared with recommendations for specialists responsible for the installation and management of traffic light objects, aiming to determine the recommended speed limit. These recommendations were developed for the proper implementation of the "Green Wave" mode in regulated traffic light systems.

Name of the organization where the dissertation was carried out. The dissertation was carried out at the "Transport Logistics and Traffic Safety" Department of Azerbaijan Technical University, under the Ministry of Science and Education of the Republic of Azerbaijan.

Structure and total volume of the dissertation. The dissertation consists of an introduction, 4 chapters, and conclusions, totaling 196 pages of computer-written text, including 13 pages of the reference list, 17 pages of appendices, and 1 page of abbreviations. The volume of each section of the dissertation is as follows: the introduction has 18,942 characters, Chapter I has 68,911 characters, Chapter II has 78,710 characters, Chapter III has 31,363 characters, Chapter IV has 29,517 characters, with a total of 227,449 characters. The dissertation includes 11 figures, 33 tables, 13 schemes, 8 diagrams, 2 graphs, a list of 126 references, and 10 appendices.

SHORT SUMMARY OF THE DİSSERTATİON

In the introduction, the topic of the dissertation is justified, and its relevance, research objectives, and the issues to be addressed are outlined. The solutions and methods for solving the problem are identified, and the scientific novelty of the research is presented. The impact of the current development of road transport on various aspects of the economy, culture, and social life is also explored. The practical significance of the research results for the application in the Azerbaijani transport system is also highlighted.

The first chapter covers topics such as the causes of traffic jams, methods for eliminating traffic congestion, the investigation of vehicle speed as a complex indicator of traffic flow, analysis of statistical data on traffic jams in Baku, the goals of the research, and directions for solving the problem.

In several studies dedicated to investigating the causes of traffic congestion in cities, it is clearly observed that traffic jams remain a problem in many developed and developing countries, posing a threat to the quality of urban life.

To eliminate the causes of traffic congestion, it is essential to use automatic data collection tools for road conditions, sufficiently flexible mathematical models of traffic flow, and software developed based on these models. Determining the average speed of vehicles is crucial for assessing road congestion. In Baku, accurate and detailed data on vehicle speeds are collected through the video detection cameras.

When investigating the causes of traffic congestion, it has been determined that traffic vehicles face congestion even during non-peak hours due to the disruption of the "Green Wave" system. The main causes of the disruption of the "Green Wave" are the improper determination of the recommended speed limits on streets and avenues, the presence of unsignalized pedestrian crossings, and the differing signal phases at controlled intersections on the streets and avenues under consideration.

As seen from the above, the issue of traffic congestion exists in most cities around the world. The reasons for the continued existence of this problem, both globally and in Azerbaijan, and the investigation into what measures need to be taken to prevent it, remain relevant topics. This research work is dedicated to the aforementioned issue, addressing all the causes outlined.

In the second chapter, topics such as the interpretation and mathematical model of the traffic congestion-delay process using the theory of mass service, proposals for eliminating the causes of traffic congestion, the study of technical regulation tools used in traffic management, the investigation of vehicle movement intensities, the determination of average vehicle speeds in Baku, traffic indicators forecasted through artificial intelligence, and the establishment of a neural network for predicting vehicle speeds are discussed.

The occurrence of traffic congestion, which results in delays for public transport at the final stop on its route, as well as the application of the "Green Wave" principle, have been considered as a unified process, and a structural model has been developed, as shown in Figure 1.

The structural model of traffic congestion, public transport delays at the final stop, and the application of the "Green Wave" regime is considered universal, as it can also be applied to streets with controlled intersections where public transport routes do not pass.

As shown in Figure 1, the following positive outcomes are expected after the implementation of the "Green Wave" system:

1. Reduction in the delay time of public transport;
2. Decrease in traffic congestion on the streets;
3. Increased passenger satisfaction and quicker arrival at the destination;
4. Reduction in the carbon dioxide emissions released into the atmosphere during time spent in traffic.

Based on this structural model, a functional relationship model has been developed between the factors affecting traffic congestion on streets and the time taken for public transport to reach the final stop.

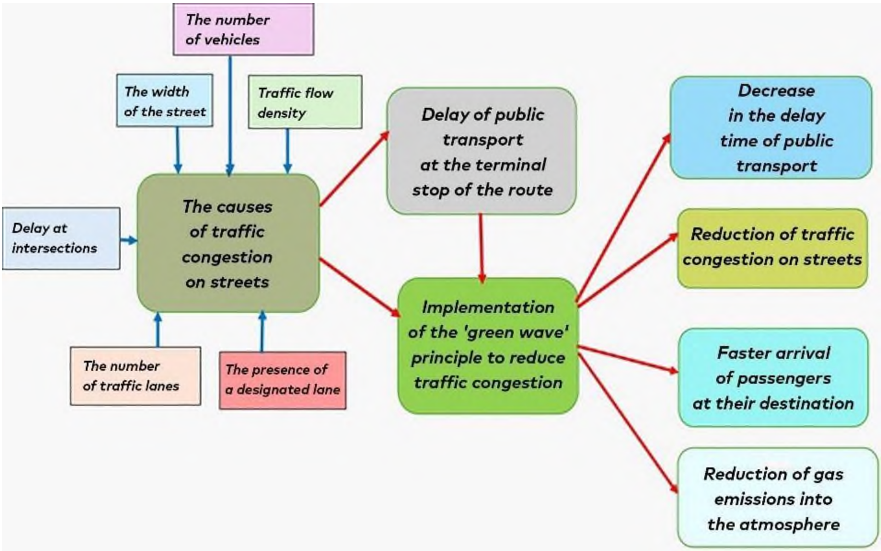

Figure 1. Structural model of the emergence of traffic congestion, delays of public transport at the final stop, and the implementation of the "Green Wave" system

The functional relationship model is shown in Figure 2[1].

As seen in Figure 2, the input parameters of the functional relationship model are as follows:

X_1 - Street width - *W, m*;

X_2 - Number of vehicles - N_v, *units*;

X_3 - Traffic flow intensity - *Q, vehicles/hour*;

X_4 - Number of lanes - *L, units*;

X_5 - Presence of a dedicated lane - *D, units*;

X_6 - Delay time at intersections - T_i, *seconds*.

The model output parameter:

Y - The time to reach the final stop of the public transport vehicle on the route – T_c, minutes.

In general, the functional model is expressed as follows in Equation (1):

[1] Yona, E., Novoselsky, A., Kagan, E. A Queueing Model for Traffic Flow Control

in the Road Intersection// – Switzerland: MDPİ, – 2022. №10 (21), - p. 1-15

$$Y(T_c)=f(X_1,X_2,X_3,X_4,X_5,X_6) \quad (1)$$

Based on the functional model, the natural general functional dependence between input and output parameters can be written as shown in Equation (2):

$$F(T_c)=f(W,N_v,Q,L,D,T_i) \quad (2)$$

To express the relationship between these parameters, we propose the following multivariable regression equation (3):

$$T=\beta_0+\beta_1 W+\beta_2 N_v+\beta_3 Q+\beta_4 L+\beta_5 D+\beta_6 T_i+\epsilon, \quad (3)$$

here:

- $\beta_0, \beta_1, \ldots, \beta_6$, T - is the total travel time along the route,
- β_0 - is the constant term,
- $\beta_0, \beta_1, \ldots, \beta_6$ - are the regression coefficients,
- ϵ - is the error term of the equation.

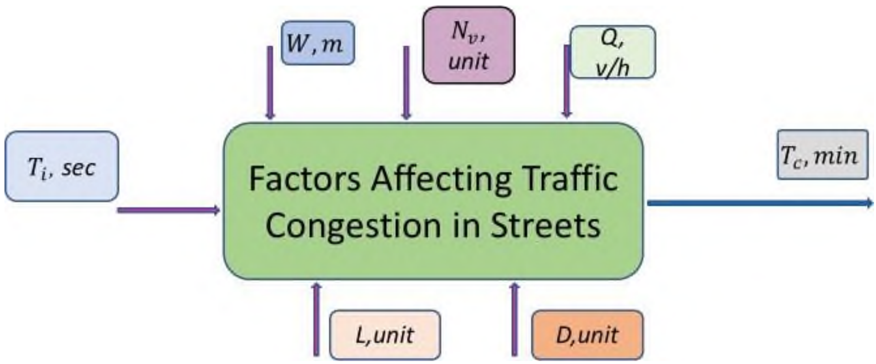

Figure 2. Functional relationship model between factors affecting traffic congestion and the time to reach the final stop

Interpretation of the elements of the regression equation individually[2]:

1. Street width (W) has a negative effect – wider streets reduce congestion and decrease travel time, so $\beta_1<0$.
2. Number of vehicles (N_v) has a positive effect – more vehicles increase congestion and increase travel time, so $\beta_2>0$.
3. Traffic flow intensity (Q) has a positive effect – higher traffic density leads to longer travel times, so $\beta_3>0$.
4. Number of lanes (L) has a negative effect – more lanes improve flow and reduce travel time, so $\beta_4<0$.
5. Presence of a dedicated lane (D) has a negative effect – if present, buses and bicycles move faster, so $\beta_5<0$.
6. Delays at intersections (T_i) have a positive effect – more delays at intersections increase travel time, so $\beta_6>0$.

Based on the data obtained from the observations conducted with reference to theoretical considerations, a regression model was established using the coefficients determined from the regression equation provided in (3), and the model was executed with a runtime of 50 minutes as specified in (4).

$$T = 50 - 1.5W + 0.005N_v + 0.02Q - 3L - 8D + 0.1T_i, \quad (4)$$

From Equation (4), it is evident that the influence of the regression equation coefficients on the travel time is different. The impact of the elements considered on the base travel time is explained as follows:

- An increase of 1 meter in the street width reduces the time by

[2] Queuing Theory: [Electronic resource] / Corporate Finance Institute. – Canada, 2025. – URL:https://corporatefinanceinstitute.com/resources/accounting/queuing-theory/

1.5 minutes;

- Each additional vehicle in the traffic adds 0.005 minutes to the travel time.
- The traffic intensity (vehicles per hour) increases the travel time by 0.02 minutes;
- Each additional lane reduces the travel time by 3 minutes;
- The presence of a dedicated lane reduces the travel time by 8 minutes;
- Each second of delay at an intersection increases the travel time by 0.1 minutes.

Let's perform the calculation for Afiyaddin Jalilov Street in Baku based on the given input parameter values:

1. Street width = 11 m
2. Number of vehicles = 2400 units
3. Traffic intensity = 1893 vehicles/hour
4. Number of lanes = 4 lanes
5. Bus-only Lane = 1
6. Intersection delay = 60 seconds

We substitute these quantities into the 4th formula and solve the equation.

$$T = 50 - 1.5\,(11) + 0.005(2400) + 0.02(1893) - 3(4) - \\ - 8(1) + 0.1(60)$$

$$T = 69 \text{ minute}$$

Under the accepted “variable conditions”, the travel time of public transportation at this intersection will be 69 minutes.

The initial results obtained through mathematical modeling fully achieve the set objective. A comparison was made to examine how the implementation of the proposed “Green Wave” regime would affect the output parameter.

Upon examining the impact of the "Green Wave" regime on travel time, it was determined that this regime synchronizes traffic lights to create a smooth congestion flow. Several key effects on travel time and density are reflected in the regression equation (3).

While the overall impact of the factors considered in the functional model was previously expressed, after conducting research and mathematical analysis, the functional model can be presented, depending on the degree and nature of the influence of each factor, as shown in equation (4).

$$F(T_c) = f(W^{-1}, N_v, Q\ , L^{-1}, D^{-1}, T_i\ ), \text{ minute} \tag{5}$$

Earlier, we used the regression model (3). To integrate the effect of the "Green Wave", we introduce the adjustment coefficient G, which reduces the intersection delay (D_i) and the intensity of traffic (Q).

Thus, considering the mentioned adjustment coefficient G, the expression of the regression model (3) will be as shown in equation (6).

$$T = \beta_0 + \beta_1 W + \beta_2 N_v + \beta_3 (Q \cdot G) + \beta_4 L + \beta_5 D + \beta_6 (D_i \cdot G) \tag{6}$$

here

G is the efficiency coefficient of the "Green Wave" regime implementation, and experiments show that it varies within the range of G = 0.5 to 1.0.

In specific cases:

G = 1.0 corresponds to the case without the "Green Wave" - at normal traffic density.

G = 0.5 corresponds to the optimal "Green Wave" - when minimum stopping and maximum efficiency are achieved.

Prior to the “Green Wave” regime, there were high intersection delays, uneven traffic flow, and long waiting times. However, after its implementation, reduced delays, smoother traffic flow, and faster public transportation are ensured.

These results provide critical insights for traffic congestion management in cities. By identifying the factors that most influence public transportation delays, the relevant city authorities can plan and optimize traffic flow, improve road infrastructure, and reduce congestion.

In addressing the main idea of the research, eight streets and avenues in the city of Baku were studied (see Figure 3), and data on the intensity of motor vehicles and traffic speed indicators were collected over a 15-day period, 24 hours a day, at 22 points on these streets and avenues.

Figure 3. Streets and avenues under research

Additionally, the following data was studied and analyzed on the streets and avenues, from the beginning of the street or avenue to the VVDS, and from the VVDS to the end of the road:

- The total length of the road;
- Traffic directions (in some sections of the road, the direction of travel may change);
- The number of traffic lanes;
- The number of controlled and uncontrolled intersections;
- The number of pedestrian crossings and grade-separated pedestrian crossings;
- The number of routes and "pocket" type bus stops;
- The number of bus and taxi stops;
- The number of car parking areas (parking spaces);
- The number of lanes occupied by parking;
- The number of points of interest, electronic boards, U-turns, and road signs;
- Indicators of the variation in the optimal cycle length for traffic control at controlled intersections, broken down by weekly, daily, and hourly changes.

In addition to the main idea of the research, the structure of several projects developed to improve road traffic safety in the city of Baku is presented in Figure 4.

Since changes in traffic speed are one of the main causes of congestion, it can be concluded that improper speed regulation affects the disruption of the "Green Wave" regime.

During the research on the prediction of motor vehicle speeds using neural networks, it was determined that neural networks have been widely used to solve problems arising in various fields.

In the construction of the "Green Wave" schedule, the recommended travel speed was determined through the prediction of traffic speeds using a neural network, for which a fully connected feedforward neural network model was employed.

Chapter three covers topics such as the construction of test corpora for predicting the velocity of motor vehicles, training the neural network, and evaluating the results of the neural network training.

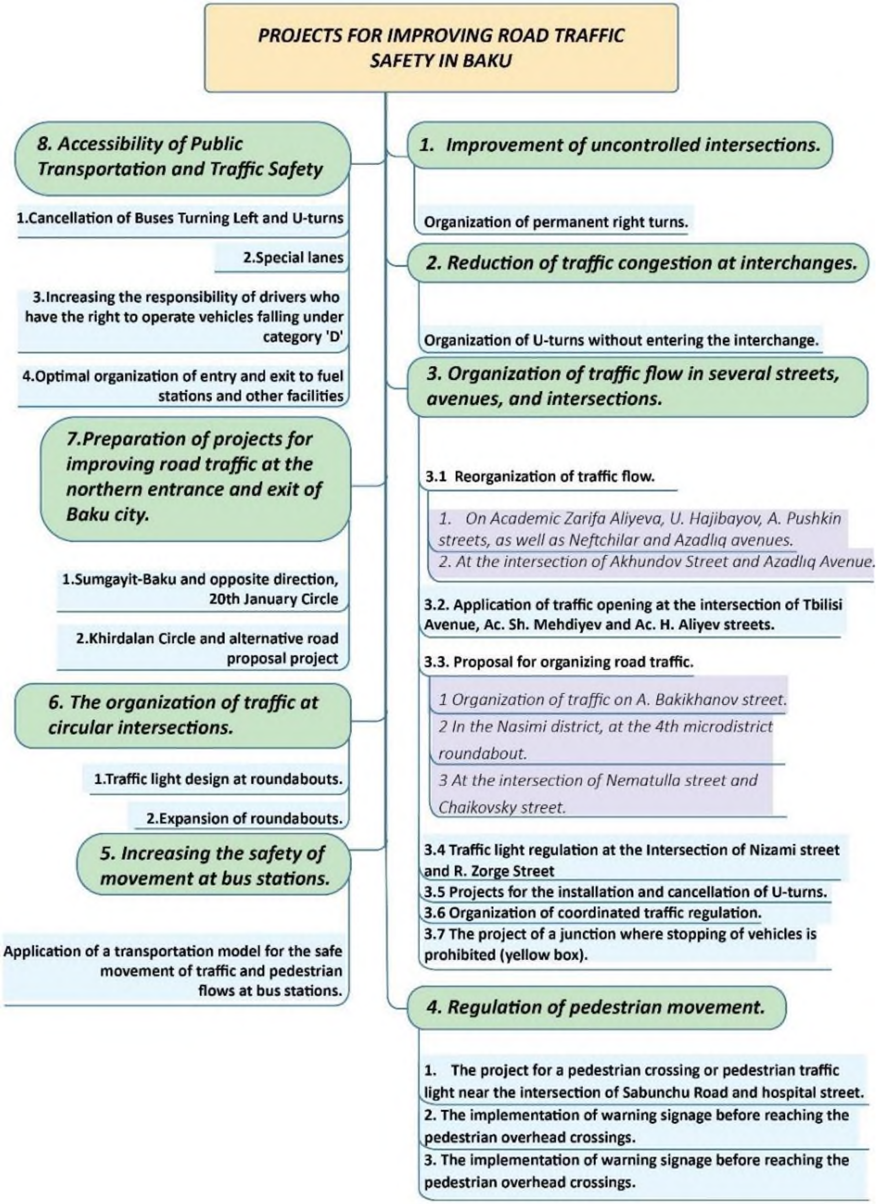

Figure 4. Structure of projects aimed at improving road traffic safety in the city of Baku

Since a neural network is a collection of individual neurons associated with a specific structure, the computational power of the network, i.e., the tasks it can perform, is determined by these connections.

Considering the current use of artificial intelligence methods in various technical fields, economics, finance, and other areas for prediction and classification tasks, the dissertation investigates the causes of traffic congestion and their elimination by forecasting traffic speed using artificial intelligence. Satisfactory results were obtained with a 4.52% error rate for previously unseen observations during the training phase.

During the preparation of the dissertation, the program for applying the neural network in artificial intelligence was written in Python 3.5. The Microsoft CNTK module was also used for training neural networks, and the script cntk_dnn.py was written in Python 3.5 for training the neural model. Additionally, the script cntk_dnn_evaluation.py was written in Python 3.5 for evaluating the trained model on the test corpus.

In accordance with the prediction of motor vehicle speeds in urban areas, observations, inspections, and analyses were conducted on several streets and avenues in the city of Baku for the purpose of evaluating the test corpus of the trained model.

For the construction of the test corpora for the trained model, data on the velocities of motor vehicles were collected and analyzed from 22 different points on 8 different roads in the capital, where VVDS were installed, over a period of 15 working days, with 24-hour data for each day.

Data was collected from the following points on the streets and avenues of Baku:

- 4 points on 28 May Street;
- 2 points on Azadliq Avenue (from the intersection with Academic Hasan Aliyev Street to Neftchilar Avenue);
- 3 points on Neftchilar Avenue;
- 2 points on Parlament Avenue;
- 6 points on Tbilisi Avenue;
- 2 points on Academic Zarifa Aliyeva Street;

- 1 point on Afiyaddin Jalilov Street;
- 2 points on M.K. Ataturk Avenue.

The total number of observation instances over 15 working days, for each of the 24 hours, at the 22 specified points, amounted to 7920, calculated as 22×15×24.

Data collected and analyzed from 18 points on 6 streets and avenues were used for training, while data from 2 points on one street (Academic Zarifa Aliyeva Street) were used for evaluation, and data from 2 points on another street (Parlament Avenue) were allocated for testing. During the reports, the observation instances were divided as shown in Table 1.

Overall, 53 road characteristics were considered in the issue of predicting motor vehicle speeds in urban areas, using the example of the city of Baku.

Additionally, considering the time indicators expressed in full hours and the vehicle speeds recorded by the VVDS, a matrix of size 7920 x 55 was obtained.

Table 1.
Division of Observation Cases

Training	Evaluation	Test	Total
7200	360	360	7920

The analysis of international practices has revealed that algorithms based on neural networks are extensively employed in transportation-related issues due to their high adaptability, robust learning capabilities, and ability to generalize. Recurrent neural networks, owing to their distinctive internal structure that enables efficient processing of data from future days, have been applied in the prediction of traffic flow.

When considering a neural network consisting of a single layer of neurons, the process depicted in Figure 5 will be designed.

The vectors {X1, X2, Xi} and {d1, d2, di} illustrated in Figure 5 represent the training pairs, wherein all parameters influencing traffic congestion, such as the distances before and after the observed point on the streets and avenues, VVDSs, infrastructure components related to motor vehicle traffic, technical regulatory devices for traffic management, optimal adjustment times for traffic signal systems, the number of phases, the number of road signs, as well as data pertaining to traffic intensity and speed on the observed streets and avenues, are incorporated as input layers. Subsequently, hidden layers, arising from the interdependencies between these parameters, are processed, ultimately leading to the determination of the average traffic speeds in the output layers as a result of the learning process[3].

Input Sample Output Sample Training

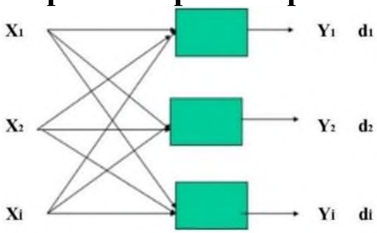

Figure 5. Learning Process of the Neural Network

In the dissertation, 53 characteristics for training and time (in full hours) are considered (a total of 54 indicators), which are normalized based on the mean and variation, and fed as input into the neural network. For the given vector $X = (x_1, x_2, \ldots, x_{54})$, the neural network predicts the velocity Y recorded by the detector at the corresponding hour, where $Y = f(X)$ is the output.

The neural network learns the parameters that minimize the error over the training set[4]. The training corpus consists of 7200 observations. All weight coefficients of the neural network are initialized with a uniform distribution in the range of (-0.02, 0.02). For continuous convergence, the learning rate is set to a constant value of $\alpha = 0.05$.

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[3] Thorsell, E. Vehicle speed-profile prediction without spatial information: / master thesis /– Gothenburg, 2018. – 81 p.

[4] Fajariyanto, E., Fajar.M. Performance of Logistic Regression and Multilayer Perceptron Neural Network in Classification of Objects // – İndia: International Journal of Scientific Research in Mathematical and Statistical Sciences,– 2021. №1, – p. 52-55.

Based on the research and calculations, the main part of the dissertation, which is the prediction of traffic flow, utilizes data from two detector camera observations on a single road from the test corpus allocated for evaluating the results of the training. During the training, different values for the number and size of the layers were examined, and it was determined that the best results were obtained when the number of layers was n = 5 and the size of the layers was 20.

Accordingly, the number of learned parameters has been determined as follows:

$$54 \times 20+20 \times 20 \times 4+20 \times 6 + 1 = 2801$$

The model provides a forecast for the average velocity for each hour of the day[5]. In order to facilitate a comparison with real-world data, the corresponding indicators for each hour across 15 working days have been established. Statistically, the average values for each hour, observed over these 15 working days, must be derived by utilizing the mean values for each respective hour, as delineated in Equation 7.

$$y_i = \frac{1}{15} \sum_{i=1}^{15} y_{i,f} \qquad i = 1, \dots, 24 \qquad (7)$$

here

$y_{i,f}$ denotes the average velocity of the vehicles recorded by the detector camera during the j-th day at the i-th hour.

In order to assess the quality of the forecast, the mean absolute error has been utilized. For this purpose, the average of the relative differences between the forecasted values and the real values for each of the 24 hours has been computed, as described below[6].

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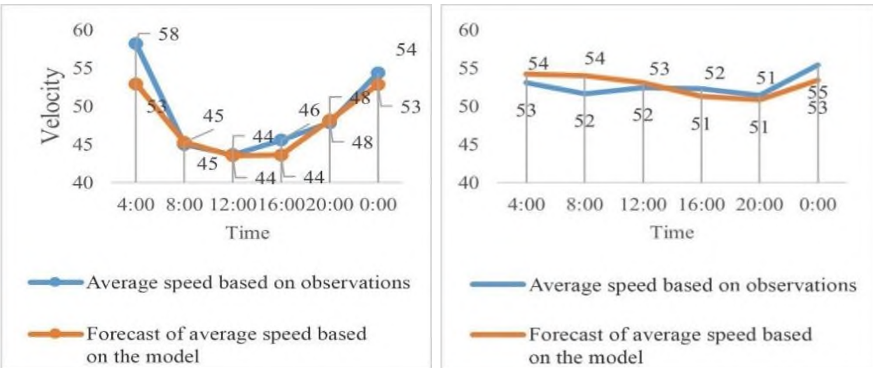
[5] Ciptaningtyas, H.T., Fatichah, C., Sabila, A. Network traffic anomaly prediction using Artificial Neural Network // AIP Conference, USA, – 2017. – p.16

[6] Belhadi, A. A recurrent neural network for urban long-term traffic flow forecasting / A.Belhadi, Y.Djenour, D.Djenouri [et al.] // Springer, – Berlin: – 2020. №50, – p. 3252-3265.

The models were evaluated and compared based on this error criterion, and it was determined that the model delivering the most accurate results exhibited a mean absolute error of 4.52%.

Correspondingly, for the test corpus, forecasts based on the velocities of vehicles observed in the VVDS at certain hours were provided, as shown in Figure 6. As indicated by the results, in some instances, the forecasts were found to be very close to the real values, with a difference of less than 1 km/h.

The observed and forecasted velocities for each detector camera, based on the model, are presented in Figure 6.



a) The first detector camera; b) The second detector camera;

Figure 6. Comparative diagram of the forecasted average velocities of vehicles based on observations and the model

The fourth chapter covers the establishment of confidence intervals for the average velocities of vehicles, the prediction of traffic indicators using artificial intelligence, the construction of the "Green Wave" traffic flow diagram on Matbuat Avenue and Academic Zarifa Aliyeva Street in Baku, as well as the justification of the expected economic efficiency from the implementation of the "Green Wave" system.

As stated in the dissertation, even during peak hours, traffic congestion is caused by the disruption of the "Green Wave" system. To address this, artificial intelligence was used, and as shown in

Chapters II and III, a speed limit with a programmed confidence interval was established with 95% accuracy and learned with high precision. The dissertation outlines the research, methodology, and solutions, with studies conducted on 8 streets in Baku. Data from 6 streets were analyzed, and the other 2 streets were tested. Furthermore, the "Green Wave" traffic flow diagram was designed for Matbuat Avenue and Academic Zarifa Aliyeva Street in Baku, and it was implemented on Matbuat Avenue.

After the relevant analyses, a diagram depicting the dependency of the average velocities of motor vehicles on the days of the month, separately for each hour of the day, was constructed (Figure 7).

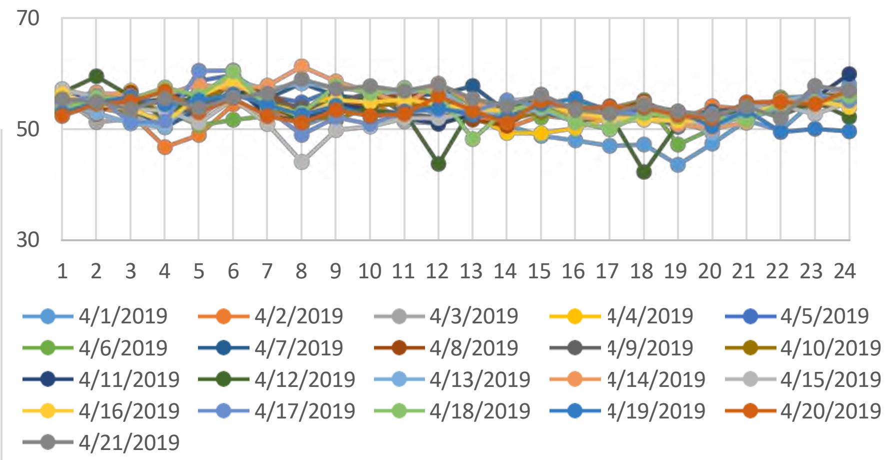


Figure 7. Comparative diagram of the average velocities of motor vehicles throughout the 21st of April, broken down by the hours of the day

For the first three weeks of April, for weekdays only, the statistical estimates of the mean, standard deviation, and skewness, as well as the quantiles for the student's t-distribution, the lower and upper bounds, and the differences between them were determined. Additionally, the degrees of freedom (df) and the confidence level were calculated (Table 2).

Table 2.
The values of other indicators with a degree of freedom of 14 and a confidence level of 95%

Time	Unbiased statistical estimate for the expected value	Unbiased statistical estimate for the standard deviation	The Studentized Range Quantile	Lower limit	Upper limit	Difference
1	55.1	1.2	2.1	54.5	55.8	1.3
2	55.1	1.9	2.1	54.1	56.2	2.0
3	54.4	1.8	2.1	53.4	55.4	2.0
4	53.2	2.5	2.1	51.8	54.5	2.8
5	54.8	3.0	2.1	53.2	56.4	3.3
6	58.0	1.8	2.1	57.0	59.0	2.0
7	54.1	1.4	2.1	53.4	54.9	1.5
8	51.7	2.5	2.1	50.3	53.1	2.8
9	54.1	2.1	2.1	53.0	55.3	2.3
10	54.0	1.9	2.1	52.9	55.1	2.1
11	53.9	2.0	2.1	52.8	54.9	2.2
12	52.5	2.9	2.1	50.9	54.1	3.2
13	52.7	1.4	2.1	51.9	53.5	1.5
14	52.4	1.9	2.1	51.4	53.5	2.1
15	53.6	2.1	2.1	52.5	54.7	2.3
16	52.3	1.8	2.1	51.3	53.3	2.0
17	51.8	1.7	2.1	50.9	52.7	1.8
18	51.8	3.2	2.1	50.1	53.6	3.5
19	51.0	2.2	2.1	49.8	52.2	2.4
20	51.5	1.4	2.1	50.7	52.2	1.6
21	53.2	1.0	2.1	52.7	53.7	1.1
22	53.6	1.8	2.1	52.6	54.6	2.0
23	54.8	1.5	2.1	53.9	55.7	1.7
24	55.4	2.4	2.1	54.1	56.7	2.6

These calculations were performed for each day of the first three weeks of April 2019, for 01:00 AM, as shown in Table 2 and carried out in the sequence outlined in the dissertation[7].

As a result of the calculations, the comparative situation arising from the difference between the upper and lower bounds of the average velocity indicators of motor vehicles throughout the 21st of April, broken down by the hours of the day, is shown in Figure 8[8].

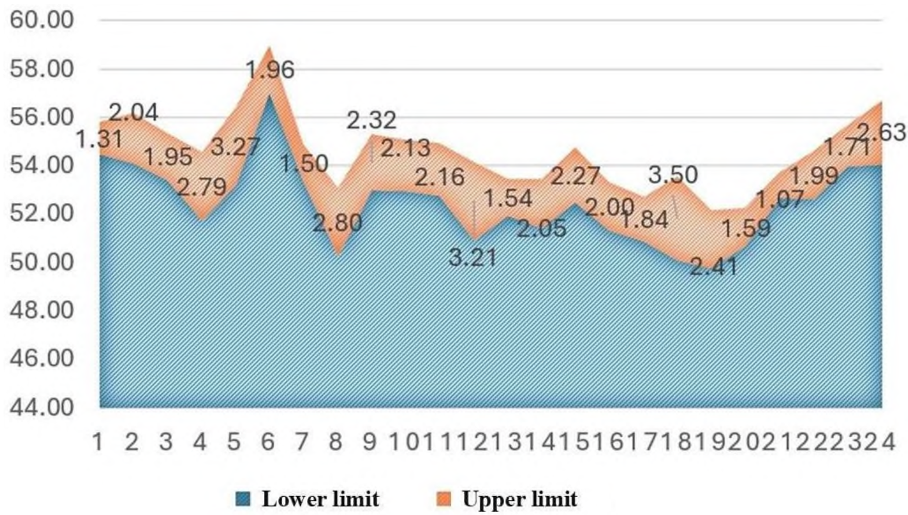


Figure 8. Comparative diagram of the difference between the upper and lower limits of the average velocity indicators of motor vehicles throughout the 21st of April, broken down by the hours of the day.

As stated in the dissertation, it is possible to determine the recommended velocity in the "Green Wave" diagram with the help of

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[7] Kart, O., Chaghri, G.O., Bashchiftchi, F. Speed Compatible Green Wave Corridor with The Internet of Things // – İstanbul : European Journal of Science and Technology, – 2021. № Special 28, – p. 411-416.

[8] Kiers, M., Visser, C. The Effect of a green wave on traffic emissions // Proceeding of: International E[55nergie wirts chaftstagung Conference Viene Technological University, – Viene: Sciences Research, – 2017, p. 7.

the artificial intelligence method. This allows for a more realistic, traffic flow-adjusted determination of the recommended velocity. At the same time, by studying the causes of traffic congestion in cities, research is conducted using the example of Baku, aiming to investigate existing statistical indicators in the field of road traffic and provide recommendations in the mentioned direction.

Following the information provided above, the results of the report on the construction of the coordinated regulation diagram at the interchanges on Matbuat Avenue for the implementation of the "Green Wave" are presented in Table 3.

Table 3.
Report on the construction of the coordinated regulation diagram

Intersections of Matbuat Avenue	T_{Cy} sec.	T_C sec.	T_a sec.	a	t_g^* sec.	t_r^* sec.	T_{CF}^* sec.
A.Sultanova st.	58	50	91	33	33	50	91
M.Rahim st.	97	89	91	-6	63	20	91
B.Vahabzadeh st.	114	106	91	-23	66	17	91
A.Hagverdiyev st.	79	71	91	12	58	25	91
A.Abbasov st.	65	57	91	26	52	31	91

here

T_{Cy} - optimal cycle lengths of regulation;

T_C - conditional cycle lengths;

T_a - calculated regulation cycle lengths;

a - the difference between the cycle lengths;

t^*_g, t^*_r – the duration of green and red light phases at intersections where the work modes are corrected;

T^*_{Cy} - total cycle length.

The dissertation also encompasses the development of several projects aimed at improving traffic safety and organizational efficiency in Baku. To achieve this, a series of studies were conducted on Matbuat Avenue in Baku, and the "Green Wave" diagram was constructed as shown in Figure 9.

As a result of the calculations performed for the establishment of the "Green Wave" system, the recommended velocity for motor vehicles along Matbuat Avenue, from the intersection with A.Sultanov Street to the intersection with A.Abbasov Street, was determined to be 55 km/h in the direction of travel and 50 km/h in the opposite direction. Additionally, the horizontal scale was set at 1 cm = 10 seconds, and the vertical scale was set at 1 cm = 100 meters. It was determined that the width of the time lane was 24 seconds.

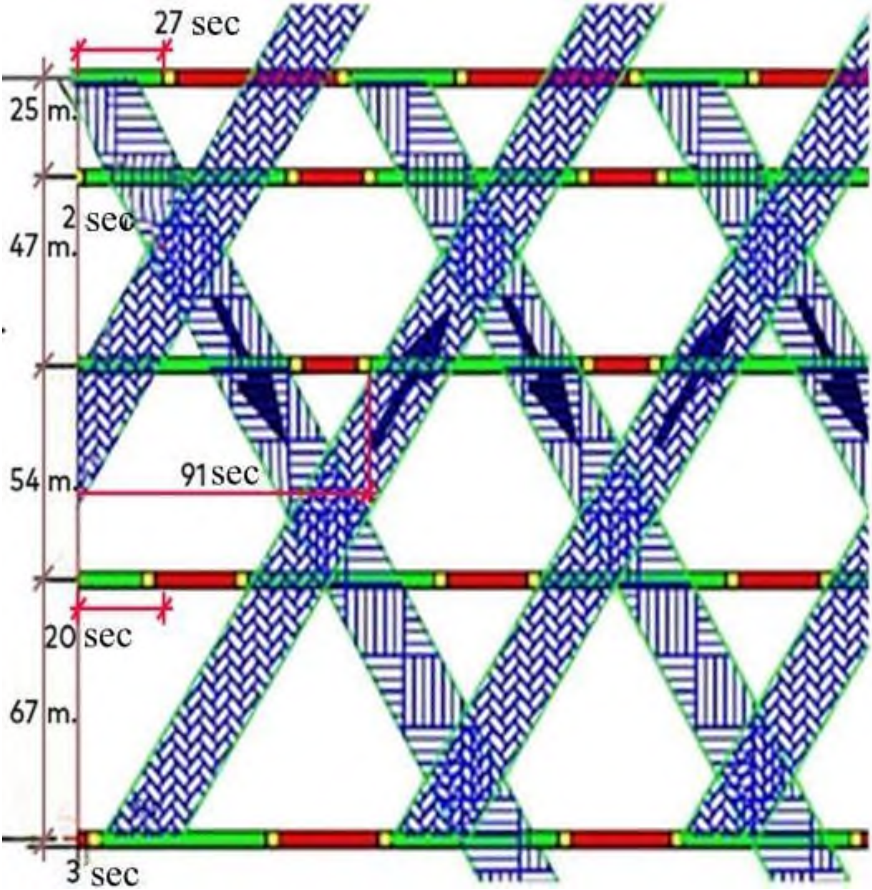

Figure 9. Coordinated regulation diagram established on Matbuat Avenue

The optimal cycle lengths of the regulation at the interchanges on Academic Zarifa Aliyeva Street are presented in Table 4.

Table 4.

Lengths of primary regulatory lanes along the streets and boulevards intersecting with Academic Zarifa Aliyeva Street

Optimal lengths of the regulation cycles	R.Behbudov Street	Bulbul Avenue	S.Vurghun Street
T_{Cy}	60	60	60

Furthermore, based on the calculations for the development of the "Green Wave" diagram, a project has been designed for Academic Zarifa Aliyeva Street, as shown in Figure 10, where the recommended vehicle speed is 50 km/h, the horizontal scale is 10 seconds per 1 cm, and the vertical scale is 100 meters per 1 cm, with a time strip width of 24 seconds.

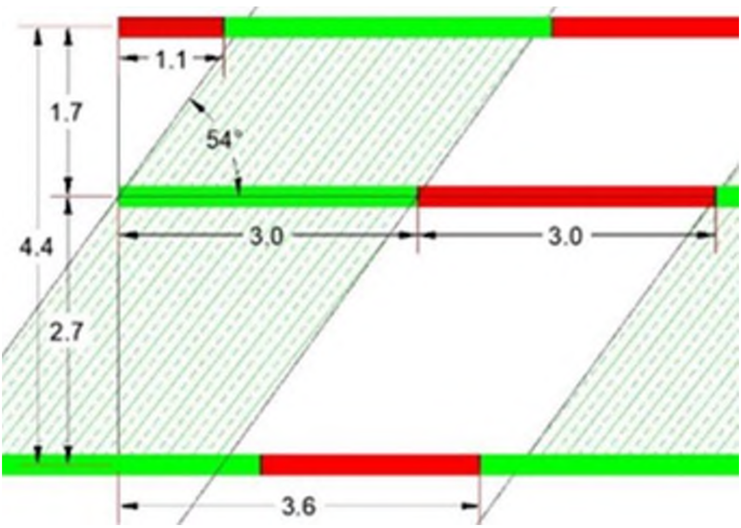

Figure 10. Coordinated regulation diagram implemented on Academic Zarifa Aliyeva Street

The economic efficiency to be gained through the reduction of time losses during the organization of continuous traffic flow on the roads has been analyzed. In the analysis, the average vehicle speed indicators on Academic Zarifa Aliyeva Street were taken for the period between 00:00 and 07:00. The number of observations is 147, covering the period from April 1st to 21st, 2019, and 8 hours of each day.

Based on the traffic flow indicators on Academic Zarifa Aliyeva Street, the adaptive “Green Wave” diagram has been constructed. As shown in Figure 11, the impact of the “Green Wave” system on vehicle speed has been determined by analyzing the changes in speed under free flow, congested, and congestion conditions (indicated by green, yellow, and red dashed lines, respectively).

Figure 11. Traffic flow conditions with adaptive regulation of the "Green Wave" regime

In Figure 11, the blue line represents the "Green Wave" regime implemented after adaptive regulation, while the red line indicates the existing speed limit on Academic Zarifa Aliyeva Street.

The upper limit of the interval is calculated as the sum of the product of the arithmetic mean and the time value at a 95% confidence level. The main purpose of calculating this interval is to express confidence in the accuracy of the data, assist in decision-making, and understand how close the results will be to the population by testing hypotheses. Based on the results obtained from the data, the confidence level on Academic Zarifa Aliyeva Street is 0.68[9]. According to this interval, as shown in Table 5, the population mean is likely to lie between 43.51 and 44.87 with 95% confidence.

[9] William.L.C. Statistics for business and eceonomics. Tenth edition/ L.C.William, N.Paul, M.T.Betty – United Kingdom: Pearson Education Limited, – 2023. – 796 p.

Table 5.

Results of economic analysis for Academic Zarifa Aliyeva Street

Mean	44.19
Standard Error	0.33
Median	44.04
Standard Deviation	1.50
Sample Variance	2.25
Kurtosis	0.00
Asymmetry	-0.14
Range	5.62
Minimum	41.20
Maximum	46.82
Count	21.00
Confidence Level (95.0%)	0.68

After analyzing the statistical indicators, it can be concluded that the implementation of the "Green Wave" regime will result in an average vehicle speed of 50 km/h on Academic Zarifa Aliyeva Street. This is 6 km/h higher than the current average speed.

By performing calculations based on the aforementioned, fuel and time savings per 1 km were calculated according to the speed limits, as shown in Table 6.

Table 6.

Fuel and time savings per 1 km according to speed limits

No	Indicator	Speed Limit, km/h		Difference	
		44	50	Physical Unit of Measurement	Value (AZN)
1	Fuel Savings	0.064 l	0.06 l	0.004 l	0.0044
2	Time Savings	1.36 min.	1.2 min.	0.16 min.	0.0187
Conclusion				0.0231 AZN	

Considering that the length of Academic Zarifa Aliyeva Street is 0.9 km and the number of vehicles passing through the street, the fuel and time savings over the course of one year, as shown in Table 7, will be as follows.

As shown in Table 7, the expected annual economic benefit of implementing the "Green Wave" project, which involves the regulation of traffic flow on the street through traffic light adjustments, is 284,156 AZN.

Table 7.

Fuel and time savings per 1 km according to speed limits

No	**Source of Savings**	**Amount of Savings** (manat)
1	Fuel Savings	54125
2	Time Savings	230031
Total	Total Savings	284156

Results

Based on the conducted research, the following solutions and recommendations have been proposed:

1. The application of technologies such as Intelligent Transport Systems (ITS) within the framework of the smart mobility concept in transportation management, as well as the analysis of various solutions aimed at addressing the underlying causes of traffic congestion, have been thoroughly examined.
2. The primary factors contributing to traffic congestion, such as road width, the number of vehicles, traffic flow intensity, the number of congestion lanes, the presence of dedicated lanes, and delays at intersections, have been identified, and a functional relationship model between these factors and vehicle travel time has been developed, with the congestion-delay process viewed as a queuing system, while a linear mathematical model was established to indicate the reduction in travel time through the application of the "Green Wave" regime.
3. Within the context of Baku city, methods aimed at addressing

the causes of traffic congestion have been investigated, focusing particularly on the regulation of traffic flow in the northern direction—an area that serves as the city's primary entry and exit point and experiences the highest intensity of congestion—as well as the promotion of public transportation usage among passengers.

4. The application of a neural network model for predicting the average road traffic flow speed, using a test corpus based on 7920 observations from VVDS units located at 22 points across 8 streets and avenues in Baku, has demonstrated that the proposed method offers enhanced capabilities for analysis and forecasting in the effective management of road traffic and road safety.

5. The research findings confirm that neural networks and artificial intelligence, particularly abstract algorithms, can be effectively applied in predicting average road traffic flow speed to mitigate the causes of traffic congestion, thereby enabling the assessment and identification of congestion risk.

6. During the research, the model developed for predicting the average road traffic speed in urban areas, using the case of Baku city, yielded positive results with an error rate of 4.52% in the corresponding test corpus. These results demonstrate that the proposed method functions independently in a real-world environment and confirm the potential for applying more complex neural networks, which would yield even better results, in future research, particularly with the importance of a larger dataset.

7. The results of the conducted research have determined that the proposed method is capable of predicting the average road traffic flow speed in streets or avenues where VVDSs or detectors are not present.

8. The solutions proposed in the dissertation will enable the organization of the "Green Wave" regime with adaptive regulation in the future, taking into account peak and non-peak hours of the day, weekends, holidays, and any other time periods.

9. As a result of the conducted research, a project for the implementation of the "Green Wave" regime was developed for Matbuat Avenue and Academic Zarifa Aliyeva Street in Baku, and the project has already been applied on Matbuat Avenue, yielding positive results.

10. The economic justification revealed that, by reducing traffic congestion and delays and increasing the average travel speed on Academic Zarifa Aliyeva Street, a total expected economic benefit of 284,156 AZN could be achieved over the course of one year, resulting from reduced fuel consumption and time savings.

The main findings of the dissertation are reflected in the following published scientific works:

1. Bağırov, M.İ. Şəhərdaxili yollarda avtobusların sol zolaqda hərəkətinin və yolayrıclarında sola və ya geri dönmələrinin ləğv edilməsi // Qloballaşma və regional inteqrasiya Respublika Elmi Konfransı, – Mingəçevir: Avrora nəşriyyatı, – 23–24 dekabr, – 2016, s. 316-317.

2. Bağırov, M.İ. Nəqliyyat vasitəsinin dayanmasının qadağan olunduğu yolayrıcı ("sarı qutu") // Doktorantların və gənc tədqiqatçıların XX Respublika Elmi Konfransı, – Bakı: Azərbaycan Dövlət Neft və Sənaye Universiteti, –24–25 may, – 2016, s. 296-298.

3. Bağırov, M.İ. "D" kateqoriyasına daxil olan avtonəqliyyat vasitələrini idarəetmə hüququna malik sürücülərin məsuliyyətinin artırılması // Azərbaycan xalqının ümummilli lideri Heydər Əliyevin anadan olmasının 94-cü ildönümünə həsr olunmuş tələbə və gənc tədqiqatçıların "Gənclər və elmi innovasiyalar" mövzusunda Respublika Elmi-texniki Konfransı, – Bakı: AzTU-nun mətbəəsi, – 3–5 may, – 2017, s. 322-323.

4. Əhmədov, H.M., Bağırov, M.İ. Dairəvi hərəkətin təşkil olunduğu bəzi yolayrıclarında hərəkətin tənzimlənməsinin təkmilləşdirilməsi // Azərbaycan beynəlxalq nəqliyyat sistemində: məqsədlər və perspektivlər Beynəlxalq elmi və praktiki Konfransı, – Bakı: Azərbaycan nəşriyyatı, – 2–5 oktyabr, – 2018, s. 110-113.

5. Bağırov, M.İ. Şəhərlərarası taksi dayanacağı // Azərbaycanın nəqliyyatı: Nailiyyətlər, problemlər və perspektivlər, – Bakı: AzTU-nun mətbəəsi, – 16–17 aprel, – 2019, – s. 100-103.

6. Bağırov, M.İ. Əliyev, İ.M. Logistik əhəmiyyətli və əhalinin sıx olduğu ərazilərdə avtostansiyaların təşkili // Azərbaycanın nəqliyyatı: Nailiyyətlər, problemlər və perspektivlər, – Bakı: AzTU- nun mətbəəsi, – 16–17 aprel, – 2019, – s. 39-41.

7. Bağırov, M.İ. Bakı şəhərinin mərkəzi hissəsində (“Hökumət Evi”ətrafında) yol hərəkətinin təşkilinin təkmilləşdirilməsi // – Bakı: Azərbaycan Respublikası Təhsil Nazirliyi, Azərbaycan Memarlıq və İnşaat Universiteti Elmi Əsərlər, – 2019. №2, – s. 59-65.
8. Bağırov, M.İ. Bakı şəhərinin şimal giriş-çıxışında nəqliyyat axınlarının tənzimlənməsi // – Bakı: Azərbaycan Respublikası Təhsil Nazirliyi, Azərbaycan Memarlıq və İnşaat Universiteti Elmi Əsərlər, – 2019. №1, – s. 130-135.
9. Bağırov, M.İ., Avtovağzal ərazisində piyadaların və nəqliyyat vasitələrinin hərəkətinin təhlükəsizliyinin təmin edilməsi üsulu, İxtira i2020 0041, Azərbaycan Respublikası / – 2020.
10. Baghirov, M.I. Prediction of recommended traffic speed for green wave regime using an artificial intelligence method // Progressive research in the modern world. Proceedings of II international traffic and practical Conference, – Boston: BoScience Publisher, – 02–04 November, – 2022, – p. 93-98.
11. Baghirov, M.I. Developing a coordinated regulation schedule to prevent damage to the environment by vehicles and improve the structure of the energy system: evidence from the city of Baku // – Kiev: Journal of Automobile transport. Collection of scientific Works, – 2023. №52, – p. 64-70.
12. Baghirov, M.I. Establishment of Confidence Intervals for Average Vehicle Speeds // – Istanbul: Journal of Traffic And Transportation Research, – 2023. №2, – p. 131-142.

The defense will be held on 29 May 2025 at 14:00 at the meeting of the Dissertation council ED 2.41 of Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at Azerbaijan Technical University

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