МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ
НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ
ФАКУЛЬТЕТ АЕРОНАВІГАЦІЇ, ЕЛЕКТРОНІКИ ТА ТЕЛЕКОМУНІКАЦІЙ
Кафедра авіаційних комп'ютерно-інтегрованих комплексів

ДОПУСТИТИ ДО ЗАХИСТУ
Завідувач кафедри
Синєглазов Віктор Михайлович
"_____"____________2021 р.

ДИПЛОМНА РОБОТА
(ПОЯСНЮВАЛЬНА ЗАПИСКА)

ВИПУСКНИКА ОСВІТНЬО-КВАЛІФІКАЦІЙНОГО РІВНЯ "БАКАЛАВР"
ЗА СПЕЦІАЛЬНОСТЮ 151 «АВТОМАТИЗАЦІЯ ТА КОМП'ЮТЕРНО-ІНТЕГРОВАНІ ТЕХНОЛОГІЇ»
ОСВІТНЬО-ПРОФЕСІЙНОЇ ПРОГРАМИ "КОМП'ЮТЕРНО-ІНТЕГРОВАНІ ТЕХНОЛОГІЧНІ ПРОЦЕСИ І ВИРОБНИЦТВА"

ТЕМА: Автоматична система управління рухом на перехресті

ВИКОНАВЕЦЬ: Пелюхівська В.Ю.

КЕРІВНИК: к.т.н., доцент Тупіцин М.Ф.

НОРМКОНТРОЛЕР: к.т.н., доцент Тупіцин М.Ф.

Київ 2021

EDUCATION AND SCIENCE MINISTRY OF UKRAINE

NATIONAL AVIATION UNIVERSITY

Department of Aviation Computer-Integrated Complexes

ADMITT TO DEFENCE

Head of the department

Syneglazov V.M.

“ ____ ” __________2021 y.

BACHELOR WORK

(EXPLANATORY NOTE)

Specialty: 151 Automation and computer-integrated technologies

Eeducational professional program "Computer-integrated technological processes and production"

THEME: Automatic traffic control system at the intersection

DONE by: Peliukhivska V.Y.

SUPERVISED by: Tupitsyn M.F.

STANDARDS CONTROLLER: Tupitsyn M.F.

Kyiv 2021

НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ

Факультет аеронавігації, електроніки та телекомунікацій

Кафедра авіаційних комп'ютерно - інтегрованих комплексів

Освітньо-кваліфікаційний рівень бакалавр

Спеціальність 151 «Автоматизація та комп'ютерно-інтегровані технології»

ЗАТВЕРДЖУЮ
Завідувач кафедри

Синєглазов В.М.
" ____ " __________2021 р.

ЗАВДАННЯ

дипломну практику студенту

Пелюхівська Валерія Юріївна

1. Тема роботи: «Автоматична система управління рухом на перехресті»

2. Термін практики з 14.04. 2021р. до 05.06.2021р.

3. Вихідні данні до роботи: Технічні параметри сучасних транспортних засобів. Технічні характеристики та алгоритм процесу функціонування світлофорів на перехресті.

4. Передумови проекту (роботи): Зосередити увагу на алгоритмах роботи світлофорів на перехресті.

5. Зміст пояснювальної записки (перелік питань, що підлягають розробці):

1. Аналіз технічних параметрів сучасних транспортних засобів та технічні характеристики процесу функціонування світлофорів на перехресті. Актуальність роботи. 2. Постановка завдання. 3. Опис методу для виконання завдання. 4. Алгоритм обробки експериментальних даних. 5. Проведення розрахунків. 6. Розробка автоматична система управління рухом на перехресті.

6. Перелік обов'язкового графічного матеріалу:

1. Структура та вигляд перехрестя; 2. Алгоритм обробки експериментальних даних роботи пропонованої системи; 3. Результаті розрахунків.

7. Розклад календаря

№	Етапи виконання бакалаврської роботи	Строк виконання	Примітка про виконання
1	Ознайомлення із завданням бакалаврської роботи	14.04.21-16.04.21	
2	Огляд та аналіз систем та алгоритмів для координованого за часом управління сигналами дорожнього руху	16.04.21-24.04.21	
3	Виберіть математичну модель рішення задачі	25.04.21-08.05.21	
4	Опис алгоритму вирішення завдання	09.05.21-24.05.21	
5	Розрахунок параметрів автоматичної системи управління дорожнім рухом. Аналіз результатів	25.05.21-30.05.21	
6	Проектування бакалаврських робіт	31.05.21–05.06.21	

8. Дата видачі завдання ___________________14.04.2021

Керівник: к.т.н., доцент _____________________ Тупіцин М.Ф.

(підпис)

Завдання прийняв до виконання __________Пелюхівська В.Ю.

(підпис)

MINISTRY OF EDUCATION AND SCIENCE UKRAINE

NATIONAL AVIATION UNIVERSITY

AVIATION COMPUTER-INTEGRATED COMPLEXES DEPARTMENT

Bachelor Educational Qualification Level

Specialty151 - "Automation and computer-integrated technologies"

APPROVE

Head of department

V.M. Sineglazov____

"___" __________ 2021

REQUEST FOR PROPOSAL

For execution the bachelor work of student

Peliukhivska V.Y.

1. Theme of the work: “Automatic traffic control system at the intersection”.

2. Term of execution of the work: from 14.04.2021 р.__till 05.06.2021 р.__

3. Initial data for the work: Technical parameters of modern vehicles. Technical characteristics and algorithm of the process of traffic lights operation at the intersection.

4. Prerequisites of the project (work): Focus on the algorithms of traffic lights at the intersection.

5. The content of explanatory notes (the list of task for design):

5.1. Analysis of technical parameters of modern vehicles and technical characteristics of the process of traffic lights at the intersection. Relevance of work. 5.2. Setting objectives. 5.3. Description of the method for performing the task. 5.4. Algorithm for processing experimental data.

5.5. Carrying out calculations. 5.6. Development of an automatic traffic control system at the intersection.

6. **List of compulsory graphical materials:**

6.1. UAV classification; 6.2. Algorithm for improving emergency landing; 6.3. Presentation of bachelor work in PowerPoint.

7. Calendar Schedule

№	Stages of execution of bachelor work	Term of execution	Note of execution
1	Acquaintance with the task of the bachelor work	14.04.21-16.04.21	
2	Review and analysis of systems and algorithms for time-coordinated traffic signal control	16.04.21-24.04.21	
3	Choose of the mathematical model of task solution	25.04.21-08.05.21	
4	Description of the algorithm of task solution	09.05.21-24.05.21	
5	Parameters calculation of the automatic traffic control system. Analysis of the results	25.05.21-30.05.21	
6	Designing of bachelor work	31.05.21–05.06.21	

8. Date of issuance of task ______________________________14.04.2021

Supervisor Ph.D., associate prof., ____________ M.F. Tupitsyn
(signature)

Task is accepted for execution ____________V.Y. Peliukhivska
(signature)

ABSTRACT

The explanatory note of the bachelor work " Automatic traffic control system at the intersection ". It consists of an introduction, four sections, general conclusions, and has: _63_ pages, _19_ figures, _5_ tables, _18 references.

URBAN TRAFFIC CONTROL, INTELLIGENT TRANSPORT SYSTEMS ROAD NETWORK OPERATIONS, VARIABLE MESSAGE SIGNS.

The aim of the diploma project: to development Automatic traffic control system at the intersection with an algorithm.

Object: the process of management of road traffic at the intersection.

Subject: algorithm of management of road traffic at the intersection.

Methods of research: methods of determination the extrema of function two variables and methods for constructing the construction of a polynomial to points, and

$m > n$.

The novelty of the work is to develop the algorithm of management of road traffic at the intersection.

The obtained results can be applied at the work of adaptive traffic light, in the design of control systems road traffic at the intersection.

GLOSSARY

UTM	Urban Traffic Management
UTC	Urban Traffic Control (computerised traffic signal control)
	intelligent transport systems
RNO	Road Network Operations
CCTV	Closed Circuit Television
VMS	Variable Message Signs
TMTM	Technical means of traffic management
TM	Technical means
ATCS	Automated traffic control systems
MS	Maintenance system
OM	Over maintenance
NLS	Nonlinear Least Squares

CONTENTS

INTRODUCTION

Over the years, a wide variety of traffic management systems have been developed for urban traffic control. Among them, computerised traffic signal control, also known as Urban Traffic Control, has become the norm for large towns and cities. In dense urban networks there are clear benefits from using computers to harmonise traffic control to balance demands and flow. Other methods involve the planned management of roadspace through lane assignment, parking controls, turning bans, one-way street systems and tidal flow schemes [1-3].

At the same time, technology is constantly evolving and has impacted every aspect of our lives, including driving. Driving on the road, as recently as 20 years ago, was a far cry from what it looks like today. In those days, driving was a tasking exercise that could seem daunting at times. You relied mainly on your wits and continuously had to go through a mental checklist as you moved around from place to place [4].

Today, technology has introduced various ways to take the edge of driving without compromising on safety. Now, there are a host of features that can actually encourage you to get into a car and just set out without a destination in mind.

These features are also an indication of what driving will look like in the near future.

In series of the European countries and USA are used next urban traffic management measures:

one-way street systems;

roundabouts and more complex traffic gyratories;

signal controlled junctions (static and vehicle-actuated);

linked, time-coordinated traffic signal control;

computerised area signal control (traffic-responsive);

signalised pedestrian and cycle crossings;

dedicated bus, taxi lanes, cycle lanes;

bus priority at traffic signals;

park and ride systems;

CCTV traffic surveillance;

“bus gates” and other access control systems;

congestion charging;

high occupancy vehicle lanes and other lane control methods;

car park information systems;

VMS-based driver information system.

In the Ukraine most of these urban traffic management measures are at beginning of development only. In particular, this bachelor work is concerned one important question of the city traffic - development of system for time-coordinated traffic signal control.

PART 1.
REVIEW AND ANALYSIS OF SYSTEMS AND ALGORITHMS FOR TIME-COORDINATED TRAFFIC SIGNAL CONTROL

Traffic congestion is a growing problem that continues to plague urban areas with negative outcomes to both the traveling public and society as a whole. These negative outcomes will only grow over time as more people flock to urban areas.

The growth of the car park in cities and the increase in traffic intensity have led to a decrease in traffic speeds, delays in transport hubs, deterioration of traffic conditions, an increase in gas pollution and noise levels in urban development, and an increase in accidents on the road network [1-7].

Four Ukrainian cities entered the top 25 cities in the world with the largest traffic jams, with Kiev ranked seventh among 416 cities in the world in terms of the intensity of traffic jams. This data is provided by the analytical company TomTom in the annual ranking Traffic Index [5].

On average, every motorist spent an extra 207 hours (8 days and 15 hours) in Kiev road traffic congestion in 2020.

All this necessitates the development of effective measures to eliminate such negative consequences, especially to reduce road traffic accidents (RTA).

It is known that about 75% of road traffic accidents occur in cities, and more than half are concentrated in areas of intersections of highways.

Therefore, the problem of organizing and traffic safety poses the most important urban transport system, the correct solution of which determines the reliability and quality of the entire city transport system and the possibility of implementing the necessary engineering and technical solutions, including reducing road accidents.

Scientists use different methods in different countries organization of traffic flows, since there is no general, universal solution to this problem. The basis for the development of effective measures is scientific research to identify the patterns of the nature of movement.

1.1. Traffic flow characteristics

Making decisions on the organization of traffic and transportation, planning the operation of transport systems, assessing the efficiency of the functioning of the road network are possible only on the basis of studying the parameters of traffic flows and the dependencies between them in specific conditions. Therefore, the collection and processing of information on the relationships between the main characteristics of traffic flows - intensity, density and speed - is an essential part of traffic management activities [8]. The main traffic parameters are shown in Table 1.1.

Table 1.1.

Road traffic characteristics	Designation	Unit of measurement	Basic formula
Intensity movement	q	car/s car/hour car/day	$q = \frac{n_t}{T}$ n_t - the number of cars that passed the road section, T observation time
Volume movement	Q		
Stream composition	P	percent or fraction of a unit	
Density flow	k	car/km	$k = \frac{n_S}{S}$

			n_s the number of cars on the road section, S - length of the road section
Occupancy	R	percent or fraction of a unit	$R = \frac{\sum t_0}{T}$ T_0 - detector busy time; T - observation time
Temporal interval	t	s	$t = \frac{T}{n_t}; t = \frac{1}{q}$
Spatial interval	d	m	$d=Vt$ V - vehicle speed
Temporary (instant) speed	V_t	m/s km/h	$V_t = \frac{\sum_1^n V_t}{n}$
Spatial speed	V_s	m/s km/h	$V_s = \frac{S}{t}$ t - travel time of a road section of length S
Specific travel time (pace of movement)	t_{sf}	min/km	$t_{sf} = \frac{1}{V_s}$
Specific delay time Specific delay time	t_d	min/km	$t_s = \frac{\sum t_{d(i)}}{\sum S_i}$, $t_{d(i)}$ *- delay time of the i-th car on the way* S_i

Traffic intensity $q\ (x,t_1,t_2)$ - it is the number of vehicles passing through any section or segment of the road per unit of time (Fig. 1.1). Most often, one hour is taken as a time interval, and, accordingly, the traffic intensity is defined as car / hour. When solving some problems, information on the daily and average annual traffic intensity is used.

One of the main features of the change in traffic intensity is its unevenness in time and space. The distribution of traffic intensity over time periods is determined by the purpose of travel and their frequency. The spatial distribution of traffic intensity is associated with the distribution of freight and passenger points, their concentration and capacity.

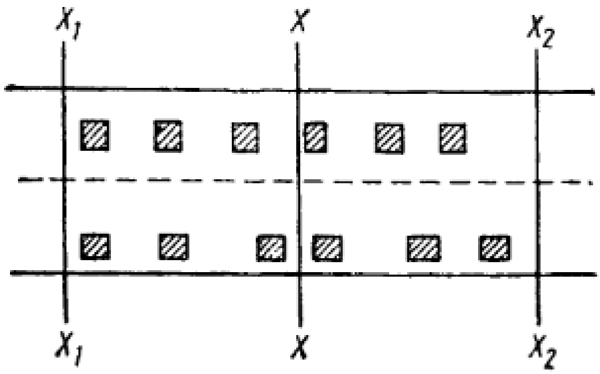


Fig. 1.1. The scheme of the movement of vehicles on the section $X_1\ X_2$ during the time $t_1;\ t_2$.

The factors influencing the formation of the need for travel are largely subject to the influence of the random component, respectively, the change in traffic intensity also occurs randomly. Therefore, the most reliable method for assessing traffic load is the systematic measurement of traffic intensity on the road network.

The most important information that guides the traffic management is information about peak loads. The change in traffic intensity during the day is characterized primarily by the presence of morning and evening rush hours. During these periods of time, there is a high traffic load, which creates significant problems for road users. During rush hour, the traffic load is about 15% of the daily.

Analysis of the change in traffic load shows that, due to the unevenness of the change in traffic intensity, inside rush hours there may be periods of time in which the intensity exceeds the average peak load. Therefore, it is recommended to analyze the traffic intensity during rush hour in five-minute periods. In this case, a peak period is distinguished - a continuous time interval during which five-minute traffic intensities exceed the average peak intensity for the entire hour (Fig. 1.2).

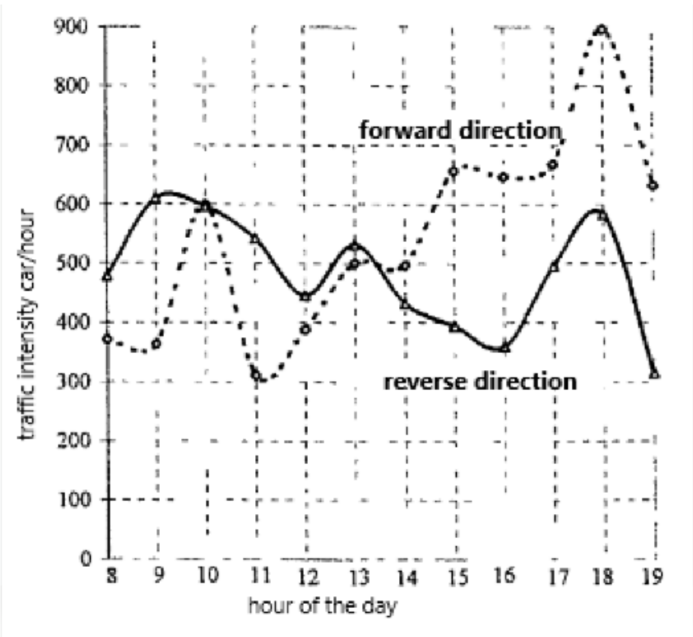


Fig. 1.2. Highlighting the peak time period

In this example, the traffic during the 15-minute peak period is 20% higher than the average traffic during the rush hour (Fig. 1.3). Ignoring this factor can lead to erroneous decisions when developing traffic management schemes.

Seasonal fluctuations in traffic intensity contribute to the formation of dense traffic flows in the summer.

Spatial fluctuations in traffic intensity are manifested in different levels of traffic load on different sections of the road network.

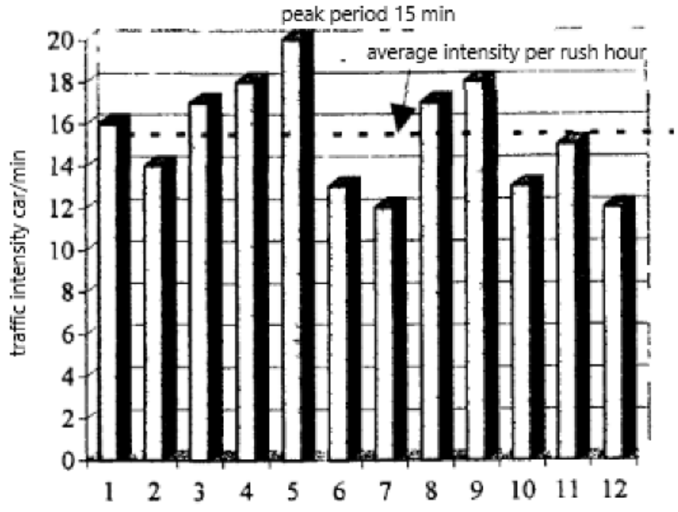


Fig. 1.3. Histogram of 5 minute intervals of movement

The unevenness of the traffic intensity is estimated by the coefficient of unevenness $K_н$, which is the ratio of the actual intensity q_f for the considered period of time to the average intensity q_c for a longer period of time:

$$K_n = q_f / q_c \quad . \qquad (1.1)$$

So, for example, the coefficient of annual inequality

$$K_n = 12q \Big/ \left(\sum_{i=1}^{12} q_i \right), \qquad (1.2)$$

where 12 – number of months in a year, q_i – traffic intensity for the month in question.

Traffic intensity affects transport costs (Fig. 1.4).

The composition of the traffic flow significantly affects the conditions and modes of movement of vehicles. Assessment of the composition of the traffic flow is carried out mainly in terms of the percentage or share of vehicles of various types. An objective assessment of the traffic load level, comparison of the load level of various highways can be made only taking into account the composition of the traffic flow.

The influence of the composition of the stream on other characteristics of road traffic is due to many factors. This is largely due to the difference in the dynamic and braking qualities of cars and trucks. Fig. 1.5 shows the normative data on the length of the braking distance for trucks and cars. During operation, these differences become even more noticeable. Therefore, in a mixed traffic flow, the likelihood of potentially dangerous situations increases.

The lower speed of movement of trucks in comparison with passenger cars forces drivers of cars to overtake in order to maintain an acceptable speed limit for them.

Maneuvering is carried out in conditions of limited visibility when a car follows a truck and also increases the risk of getting into an accident.

All these aspects made it necessary to apply the coefficients of reduction to a conventional passenger car. The determination of the values of the reduction coefficients is based on a comparison of the dynamic dimensions of various types of vehicles. The dynamic dimension of the vehicle D is the segment of the road that includes the length of the vehicle and the distance necessary to safely follow the vehicle in front. (Fig. 1.6).

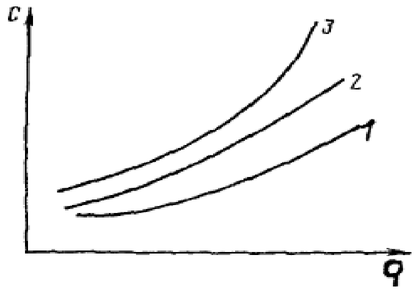


Fig. 1.4. Change in costs C for mileage depending on traffic intensity *q*: 1 - passenger car; 2 - truck; 3 – road train

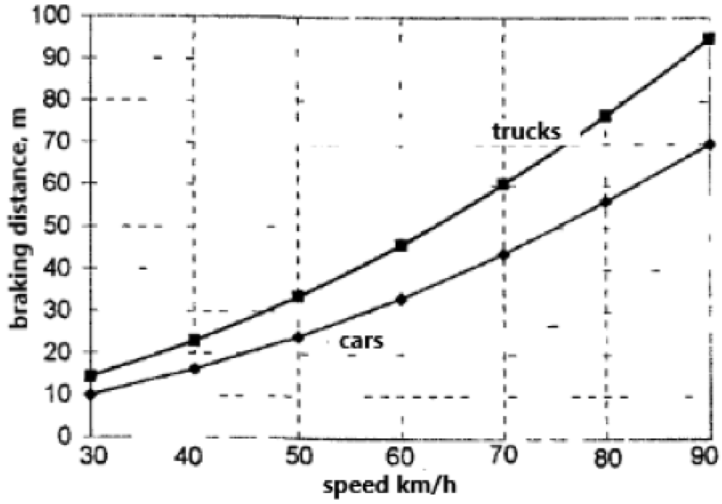


Fig. 1.5. Standard values of braking distance of cars and trucks depending on speed

The calculation of the traffic intensity in the given units is made according to the formula

$$q_{\text{пр}} = \sum_{i=1}^{n} q_i K_{\text{пр}_i} , \qquad (1.3)$$

where q_{np}- is the traffic intensity in reduced units,

q_i - traffic intensity of type i cars , K_{npi} - the coefficient of reduction of cars of the i-th type

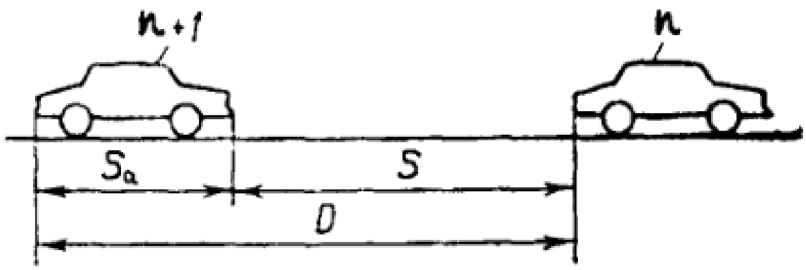


Fig. 1.6. Dynamic vehicle dimensions

The importance of using reduction coefficients in solving practical problems of traffic management is evident in the analysis of traffic load on two road sections. On the first section, with a total traffic intensity of 500 vehicles / h, the distribution of cars by type is as follows: cars - 400, freight with a carrying capacity of up to 2 tons - 80, buses - 20. On another section, with the same traffic intensity of 500 vehicles / h, the composition of the flow differs: cars - 200, trucks up to 2 tons - 100, trucks from 2 to 6 tons - 100, road trains up to 12 tons - 60, buses - 40. Taking into account the composition of the flow, the traffic intensity in the given units in the first section is 570 vehicles / h, on the second - 760 vehicles / h.

Depending on the prevalence of a particular type of vehicle in the flow, the traffic flow is conventionally classified into one of three groups: mixed flow (30-70% of cars, 70-30% of trucks), mainly trucks (more than 70% of trucks), mainly passenger cars (more than 70% of passenger cars).

The density of the traffic flow $k(x_1, x_2, t)$ is determined by the number of vehicles per 1 km of the road lane. The unit of measurement for the density of the traffic flow is car / km. With an increase in the density of traffic flow, the distance between cars decreases, the speed of movement decreases, the intensity of the driver's work increases, and the driving conditions worsen. The maximum traffic density is achieved in congestion situations. The numerical values of the maximum density are determined by the composition of the stream. For a mixed composition of the traffic flow, it is about 100 vehicles / km, for mainly passenger cars - up to 150 vehicles / km.

The main difficulties in using information on traffic density are associated with the difficulty of directly measuring this traffic parameter.

In the organization of road traffic, depending on the methods of measurement and calculation, a certain terminology has developed when characterizing the speed.

Temporary (instantaneous) speed - the speed of a vehicle in any section of the road. Measurement of the instantaneous speed does not present any difficulties, since a variety of measuring instruments are used in this case: a stopwatch that records the passage of the measured section; video camera; radar; transport detector. You can also measure the speeds of many vehicles in traffic to get reliable results. Therefore, instantaneous speed is most widely used in the practice of traffic management.

Spatial speed evaluates the change in speed along the length of the highway. The most complete characterizes the traffic conditions on the road network. However, such information can only be obtained by continuously recording the speed using a road research laboratory. The reliability of the measurement results is ensured by multiple passes along the investigated highway.

The speed of movement is assessed only taking into account the time of movement of the car along the road network.

The speed of the message is determined taking into account the delays in movement.

Based on the data on the speed of the traffic flow, it is possible to determine such a specific indicator as the rate of movement - a value inverse to the speed of the message. The pace of movement estimates the time it takes to travel a unit of route length and provides visual information about the conditions for organizing traffic and transportation.

In general terms, the relationship between intensity, density and speed is described by the basic equation of the traffic flow:

$$q = kV, \tag{1.4}$$

where q is the traffic intensity, k is the density of the traffic flow, v is the speed of the traffic flow.

The corresponding graphs are shown in Fig. 1.7.

The plot of the relationship between intensity and density is commonly referred to as the main traffic flow diagram. This graph traces the main patterns of changes in the state of the traffic flow. The first boundary point corresponds to zero intensity and density and characterizes free traffic conditions. Initially, an increase in density causes an increase in traffic, and this process continues until the capacity of the road is reached. A further increase in density leads to a significant deterioration in traffic conditions, the occurrence of congestion situations, and a decrease in traffic intensity. A further increase in density leads to a significant deterioration in traffic conditions, the occurrence of congestion situations and a decrease in traffic intensity.

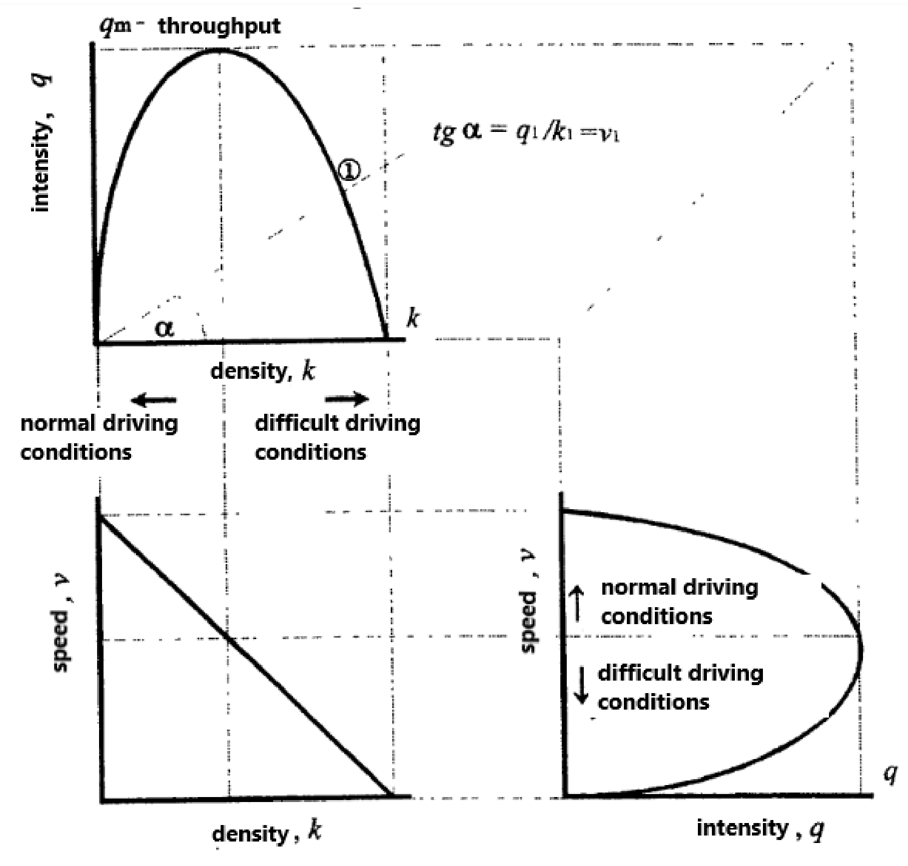


Fig. 1.7. Relationship between intensity, density and speed

Based on the main equation of the traffic flow, the tangent of the angle of inclination of the radius vector drawn from the origin of the main diagram to any point on the graph (in this case, point 1), shows the speed of movement at a given intensity and density.

Movement delays are characterized by the loss of time when a vehicle passes a given section [l_1, 1_2] with a message speed below the optimal one:

$$\Delta T = \int_{l_1}^{l_2} (1 / v_\Phi - 1 / v_0) dl, \quad (1.5)$$

where v_ϕ;v_o - the actual and optimal message rates, respectively.

The optimal speed in this case should be considered the speed of the message, which ensures a minimum loss of time, fuel, costs associated with vehicle wear, losses from road accidents, etc. In view of the difficulty of determining the true value of the optimal speed in the practice of organizing traffic, the allowed (calculated according to the safety condition) speed on a given road section is conventionally taken as the optimal one.

Waste of traffic flow

$$T = \sum q \Delta T, \quad (1.6)$$

where Σq - total traffic intensity.

Distinguish between delays on the tracks and intersections. Delays on the tracks are the result of maneuvering, the presence of cars in the stream moving at low speeds, pedestrian traffic, stops and parking of vehicles, oversaturation of the stream. Intersection delays are the result of the need to allow traffic and pedestrian flows in intersecting directions.

Taken together, all these dependencies make it possible to predict changes in the state of the traffic flow and throughput when planning measures to improve the organization of traffic and the development of the road network.

1.2. Systems and algorithms for time-coordinated traffic signal control

With regard to the transport process, the structural diagram of the system for the operation of automotive equipment [10], with some conventions, can be represented as consisting of four main elements: "driver-car-road-TSSDD (environment)" (Fig. 1.8).

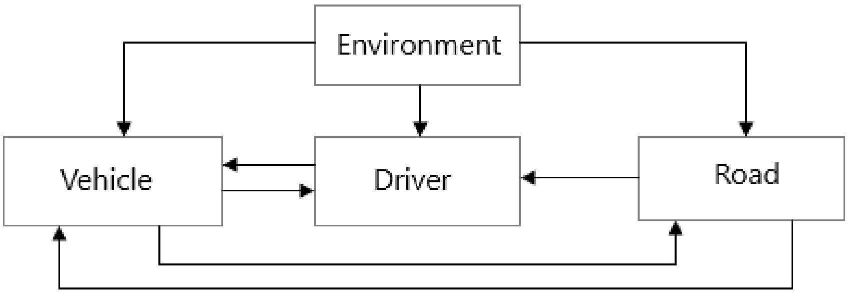


Fig. 1.8. Block diagram of the system for the operation of automotive equipment

The road has its own parameters. These include: the width of the carriageway, configuration in plan and profile, condition of the pavement, boundaries (sidewalk, ditch, shoulder). The road is related to vehicles located on it and in the roadside space, pedestrians, animals, traffic lights, road signs and markings, fixed obstacles. The road design and the level of traffic management can make it easier or more difficult for the driver to work and thus have a direct impact on his reliability. The driving environment is characterized by illumination, humidity, temperature, wind, dustiness, visibility, as well as solar geomagnetic activity and barometric pressure drops. The driver must be protected from most of the negative influences of the environment by the appropriate technical equipment of the car. The main operator of this system is undoubtedly the driver, who must always foresee what situation he may find himself in and know how to act in it.

The driver must quickly and accurately respond to stimuli, assess the value of the surrounding objects, the technical data of the car he is driving, make the right decision to maneuver the vehicle. Often the driver has to act instantly in order to prevent a traffic accident.

1.2.1. Classification of technical means of traffic management

Technical means of traffic management (TMOTM) are designed to regulate the movement of traffic and pedestrian flows. Regulation (from the Latin regula - norm, rule) of traffic management is the maintenance at a certain level of indicators of pedestrian and traffic flows, in order to ensure the efficiency and safety of road traffic.

By purpose, technical means are divided into:

- means of informing road users, namely, traffic lights, road signs and signs, road markings, guiding devices (Fig. 1.9);

- devices that ensure the normal functioning of information media (controllers, detectors, devices for processing and transmitting information, dispatching communications, computers, etc.).

Considering the means of information from the standpoint of its main user - the driver, one can conditionally divide them according to *the formation of knowledge and the place of receipt.*

From the standpoint of knowledge formation, information can be classified as follows:

- a priori (experimental) professional information that forms knowledge of the laws of the road traffic, skills in driving a vehicle, etc. Its formation occurs in the process of training and all subsequent professional experience;

- macro information that forms knowledge about the direction of travel to achieve the goal of the trip;

- micro information that forms knowledge about the driver's choice of the operational mode of movement.

Fig. 1.9. Means of informing road users at the intersection

At the place of receipt, information can be on road and off-road traffic.

The role of off-road information in the efficiency and safety of traffic is, first of all, in the creation and increase of the level of a priori information.

Macro information. The bottleneck in the traffic management is currently the low information provision of road users with means of traffic management and organization.

Macro information forms drivers' knowledge of the direction of travel. Lack or complete absence of this type of information leads to a number of negative consequences.

According to foreign data, in the UK, due to unsatisfactory placement of road signs, lack of road lighting, and other things, 28% of all accidents occur, the overrun of cars caused by mistakes of drivers when choosing the direction of travel is 4 - 6.5% of the total mileage, additional fuel costs at the same time they amount to about 1100 million liters per year. According to preliminary economic estimates, the development of a driver information system (orientation, information about meteorological conditions, danger zones in the direction of travel, etc.) in the UK will save about £ 2 billion in year. Thus, the problem of improving the information support of road traffic seems to be relevant and its solution will significantly reduce the total losses of road transport.

Macro information, which is controlling in nature, can be divided into two types: orientation and pointing**.** Recently emerging car navigation systems belong to the class of information and orientation systems, which are automated personal systems that help specific drivers in choosing the most optimal route. The filling of the vehicle fleet with such systems is proceeding at a high rate.

Progress in radio electronics, computer technology and informatics has provided a fairly broad development of information and navigation systems in road transport. Car navigation systems, which take their name from maritime and aviation terminology, can be attributed to the next generation of automated traffic control systems (ATCS). Their use allows reducing the time and cost of the trip and, in addition, enables the driver to quickly adjust his route.

Such systems are built according to the following logical algorithm:

1) determination of the spatial coordinate of a given technical means on the road network at a given moment in time;

2) determining the route of the vehicle from the location to the destination and bringing this route to the driver;

3) providing the user in the vehicle with the ability to transmit and receive information with display on the display (or in another form).

The use of navigation systems should be considered as a resource-saving factor in road transport. The effectiveness of the use of such systems consists primarily in minimizing the travel time, fuel economy, reducing the level of environmental pollution, depreciation costs and reducing the psychophysiological stress of drivers. The proliferation of car navigation on a massive scale allows for the optimal distribution of traffic flows along the road network and improves traffic safety.

With the constantly increasing traffic intensity and the production of car models with ever increasing dynamic characteristics, the problem of improving safety systems and reducing economic losses in road traffic arises. One possible solution to this problem is to improve the traffic information system.

In recent years, there has been a tendency abroad to introduce elements into the traffic information system designed to transmit to road users information necessary for planning and choosing a route. In other words, information that provides *orientation* for road users.

Drivers now have wide access to various sources of information that help them reach their destination in the shortest and safest way. This also includes road signs of directions of movement.

Until now, such aids for the most part served only as additional conveniences for drivers, since it was possible in most cases to get to the destination without resorting to their help. However, today this situation is constantly changing due to the increase in the number of vehicles and the increase in traffic density. For a number of reasons, such as the need to save fuel and time, traffic information is becoming more and more relevant.

The target function of road traffic is to move goods and passengers quickly, economically and safely. Implementation of the objective function is possible if there is a route connecting the starting and ending points of the trip. The possibility of choosing alternative routes implies solving an optimization problem in order to choose the optimal route according to a given criterion, but it is not enough just to calculate the route, it is also necessary to ensure the conditions for its observance, since a positive effect can be achieved only if the movement of vehicles is precisely along these lines. optimally calculated routes. Thus, the task of indicating the route of movement is the logical completion of the set optimization task.

Deviation from the optimal route inevitably leads to overhead. Foreign experiments have shown that the time spent on moving from the starting point to the given one with the available traffic information support can exceed the optimal one by more than 2 times, while the fuel consumption is 35%, and the car mileage is 30% or more higher than the optimal value. (with an ideal route). Moreover, the likelihood of deviating from the route increases if the driver follows this path for the first time. In this regard, along with other urgent tasks of traffic management, it is necessary to consider the task of creating an orientation system for drivers who are on unfamiliar routes.

The tasks of organizing traffic today have become so complicated that effective management of it cannot be provided only with traditional elements of the traffic information system - road signs and direction signs, road markings, traffic lights and guiding devices. Affects, on the one hand, the limited ability of the driver to perceive traffic information due to the so-called "lack of time", in which the person driving the vehicle is constantly located. On the other hand, the limited capabilities of the media in terms of types and, most importantly, the efficiency of the transmitted information affect.

In the context of the increasing complexity of the city's street and road networks and the traffic management system imposed on these networks, it becomes more and more necessary for the driver to obtain information of a strategic nature, on the basis of which he can assess and predict the situation on the forthcoming route. In this regard, the goal of developing the principles of organizing a route guidance system and informing drivers, which helps them in choosing the most optimal route, also becomes relevant. Such systems belong to the class of navigation systems. Their main purpose is to minimize travel time and cost.

1.2.2. Algorithmic regulation and smart traffic lights

Smart traffic light is a system of dynamic control of traffic signals, thanks to which, the throughput of traffic flows on the road network is improved [11].

Such technologies are beginning to be actively implemented in megalopolises and significantly change traffic, reduce accidents [12].

Modern algorithms easily find stolen cars, predict traffic congestion, and help to avoid them in advance.

Traffic lights are connected to a computer, the program on which decides how these traffic lights should interact at the current moment, depending on the current traffic situation.

The usual local traffic light mode with a fixed cycle (FC) is the usual mode intended for a stand-alone traffic light operating according to a predefined scenario: for morning rush hour, for daytime traffic, and for evening rush hour.

There is also an algorithm for coordinated traffic light control, when several traffic lights, interacting with each other, for example, on an outbound highway, provide optimal traffic management for cars.

The program generates the synchronous operation of traffic lights in order to pass a certain number of cars, maintain a given traffic intensity on a particular road section.

There is a so-called adaptive traffic light mode (AT), when the traffic data received by the computer allows traffic lights to adapt to the current traffic situation. The data comes from sensors or induction loops.

Most of the intersections equipped in this way have sensors installed in their roadways. As a result, the traffic density is automatically determined, as well as the types of cars approaching the intersections.

If, for example, public transport (bus, trolleybus or tram) is seen in the general traffic, then a green light turns on at the intersection, allowing it to pass first, while other motorists are forced to give way.

The duty shift is responsible for centralized control from the situation center. This allows the attendants, if necessary, to intervene and carry out the regulation manually, to adjust the traffic flow in the most loaded directions.

A variety of sensors are installed on the roads that quickly collect information about vehicles and the current traffic congestion in order to optimally regulate traffic.

The sensors are installed on highways, at intersections, in some places they are built into the asphalt - these are the so-called induction loops that act as an electronic regulator, allowing, for example, to automatically turn on the green light of a tram. The sensors count vehicles in separate lanes and allow calculating the traffic flow for each lane.

A large number of photo-video-fixing complexes are installed in places with a high accident rate in order to monitor the traffic situation in real time.

In addition, the backlighting of the racks is used, on which the traffic lights themselves are installed. Often billboards distract the driver's attention, and he simply does not notice the traffic light.

Traffic light pole lighting solved this problem. Now the driver can notice the traffic light even in rain or fog. This made it possible to reduce accidents in very dangerous areas for pedestrians.

An LED strip and signs with their own illumination are installed on the traffic light support, in addition, special spotlights directly illuminate the pedestrian crossing (the zebra crossing itself) and the adjacent sidewalk area where pedestrians can be.

Algorithmic traffic light regulation forces car drivers to give way to public transport: a green light for a tram or bus turns on regardless of the traffic load.

At the same time, trams move on their routes a quarter of the time faster than it was without "smart" regulation, and trolleybuses - twice as fast. So, if earlier only one bus (tram, trolleybus) could pass one intersection of a megalopolis per unit of time, today four pass by during the same time.

1.3. Problem statement

In connection with the rapid growth of the car park and increasingly wide of their use the task of algorithms and systems development for adaptive signal traffic is becoming very important.

For the improvement of the road situation in Ukraine cities and safety of the cars motion, it should be decreased downtime in road traffic congestion by new adaptive systems of signal control on intersects.

The objective of this work is to determine the optimal mode of operation of traffic lights at busy city intersections to reduce the number of traffic jams, i.e. reducing the time of unproductive work of car drivers.

As the optimization criterion, which must be minimized, we take the total idle time (delay) of all cars at the traffic light at the intersection. At the same time, the idle time includes not only the waiting time for the permitting movement - the green signal of the traffic light, but also the loss of time due to the decrease in the permissible speed of vehicles, beginning from a given distance to the intersection.

So, to decide this task it is necessary fit detectors of moving vehicles as on given distance to the intersection, as and immediately near it.

We cannot control the total idle time (delay) of all cars at the traffic light at the intersection, but with the help of the traffic light we can control the quanlity difference between vehicles that interfere with each other when passing the intersection.

PART 2.
MATHEMATICAL MODEL OF TASK SOLUTION

From the technical means, which have to detect the time spent by the vehicle at the intersection, detectors have been selected in this work (Fig. 2.1).

There are two types of detectors at the intersection: D1 and D2. D1 detectors are located at the entrance to the intersection. They read the numbers of the cars at the moment of passing through them and enter the numbers into the memory of the computing device. D2 detectors are required to account for vehicles leaving the intersection and are located directly at the border of the intersection [12].

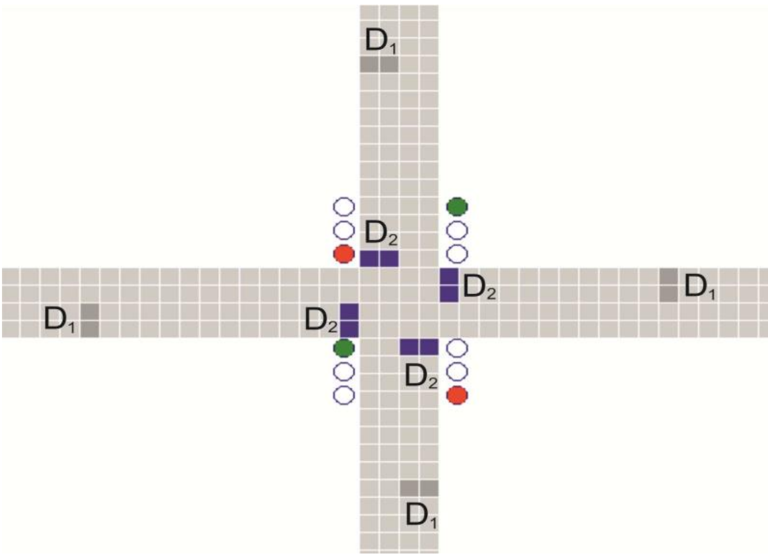


Fig. 2.1. Configuration of detectors placement on simple signalized network

Signal phasing is the basic control mechanism by which the operational efficiency and safety of a signalized intersection is determined. The current developments in signalization technology provide increasingly flexible, but inevitably more complex, signal phasing options. It is therefore important to understand clearly how traffic movements and signal phases relate to each other.

The interaction between detectors and traffic lights is as follows:

1) an identification number is read for all vehicles in the system (for example, state registration number, etc.);

2) during the operation of the red phase of the traffic light, the D1 detectors read the numbers of the cars passing through them and record them in the list according to the formulas (2.1)

$$\begin{cases} l_1 = l_1^{'} + l_3^{'}; \\ l_2 = l_2^{'} + l_4^{'}; \end{cases} \quad (2.1)$$

where l_1, l_2 – queue of horizontal and vertical roads, respectively, l'_1, l'_3 and l'_2, l'_4 – queues in each direction for each of the intersecting roads;

3) at the moment when the green light comes on, detector D1 stops writing license plates to the list, and detector D2 starts deleting numbers of cars passing through it from the list;

4) at the moment when the last of the cars passes through the detector D2 and the list becomes empty, the traffic light switches to the red phase and goes to the beginning of the cycle;

5) this rule is true for both roads.

In the course of the work, the values of the queues were determined at each traffic light switching cycle. The length of the queue was determined as follows: while the traffic light is on, a queue of cars accumulates on the road with the prohibitory signal turned on. For each direction, it is determined by the formulas

$$L_1 = \frac{\Sigma l_1}{n}; \quad L_2 = \frac{\Sigma l_2}{n}, \qquad (2.2)$$

where L_1, L_2 – the average value of the queue length over the considered time interval (the number of iterations); l_1, l_2 – the values of the lengths of the queues at each switching of the traffic light from red to green; n – number of switching from red to green during the considered period of time.

The underlying movement and phase concepts [15] are described first before various movement parameters are defined below.

Each separate queue leading to the intersection and characterized by its direction, lane usage and right of way provision is called a movement. The allocation of rights of way to individual movements is determined by the signal phasing system. The movements from each approach road are described according to their unique right of way (phasing arrangement) and lane allocation/usage characteristics.

Signal phase is a state of the signals during which one or more movements receive right of way. Signal phases will be defined in such a way that when there is a change of right of way, that is when a movement is stopped and another started, there is a phase change. A phase is identified by at least one movement gaining right of way at the start of it and at least one movement losing right of way at the end of it in the past. One complete sequence of signal phases is called a signal cycle. An example of a cycle diagram is given in Fig. 2.2.

The time from the end of the green period on one phase to the beginning of the green period on the next phase is called the intergreen time (/).It consists of yellow and all-red periods. During the all-red period, both the terminating and the starting phases/movements are shown red signal simultaneously.

It is seen that the phase *change times* (F) are defined as phase termination times which occur at the end of the green period, and the intergreen period is the initial part of the phase. Therefore, the green period starts at time (F + l).

If the *displayed green time* for a phase is G, then the green period ends at time (F + I + G). This is the phase change time for the next phase. The cycle diagram can be constructed by setting the first phase change time to zero and adding

the (l + G) value of the first phase to find the second phase change time, and so on.

The sum of all phase intergreen and green times is the *cycle time*:

$$c = \Sigma(I + G).$$

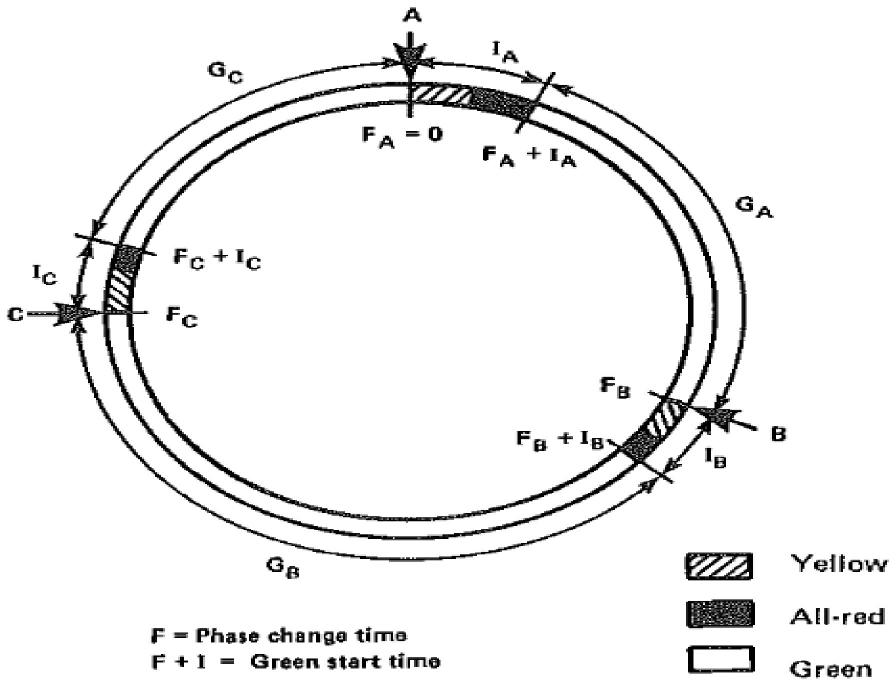


Fig. 2.2. Signal cycle diagram (for the example in Fig. 2.1)

The basic movement characteristics are illustrated in Fig. 2.3 in relation to a corresponding signal phasing arrangement. An important aspect of Fig. 2.3 is that the two phase change times (F_i, F_k) to start and stop the movement under consideration do not need to correspond to consecutive phases because it may be an overlap movement.

2.1. Choose of the mathematical model for task solution

Due to the presence of a large number of random factors affecting the movement of a vehicle in the urban transport network, a number of researchers apply stochastic approaches to the study of traffic when developing new TSODD.

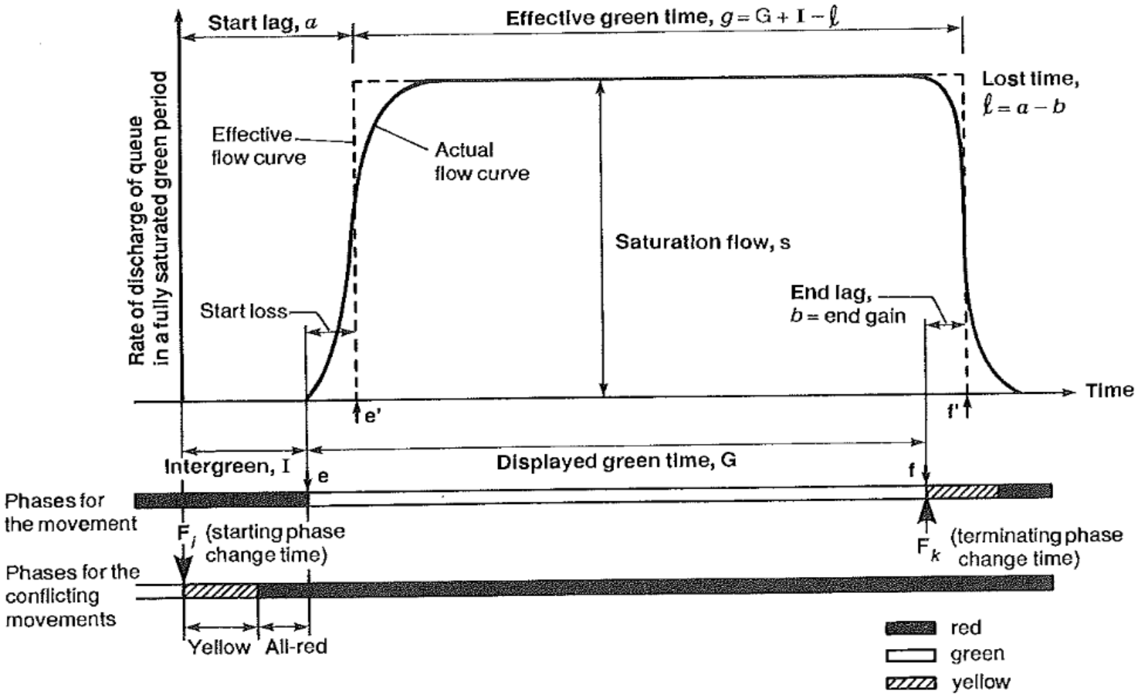


Fig. 2.3. The basic movement characteristics on the intersect

One such approach is to use the Monte-Carlo method. However, the quality of the resulting estimates will depend at least in part on factors such as quality and quantity of the available data, the algorithm used to solve, for example, the Nonlinear Least Squares (NLS) problem or method of moments. A comprehensive answer to the questions raised here is not available, but at each case it is necessary to consider concretive street traffic network.

Although the simulation study presented in this paper [13] is limited, it appears that the prediction model provides valuable information for the development of real-time traffic-adaptive signal control logic. Authors believed that: “Further study and evaluation are required before the limitations and properties will be fully understood. It is the author's belief that different prediction algorithms will be required for different situations. In some cases the use of upstream detectors will be sufficient to provide the desired level of performance. In others, more complex algorithms will be required. In still others, prediction will not be possible.”

New approach to research the relationship between the traffic intensity of vehicles and the load of intersecting roads by the length of the queue of vehicles when using various algorithms of traffic light regulation is proposed in [12]. This paper presents the results of studies carried out using micromodeling, based on the theory of cellular transport automata (TCA), to study the influence of the traffic intensity of cars and the load of intersecting roads on the length of the queue of cars when using various traffic light control algorithms. Also, in [12], based on a series of computational experiments, the efficiency is determined operation of a traffic light that supports the ability to connect adaptive algorithms for intersections with varying intensity and load.

As an assessment of the efficiency of traffic lights, a comparison of the traffic intensity values at the intersection is carried out for traffic light mode with a fixed cycle and adaptive traffic light mode.

To date, all methods for automatic estimation of turning movement proportions have used prediction error minimization methods, in which one first specifies a model for predicting the intersection's exit counts using the intersection's input counts and a trial set of turning movement proportions

(see Fig. 2.1). One then selects as the estimated proportions those values that minimize some measure of the difference between the predicted and the actual exit counts.

Other method is in using Neural Network Models [14]. The relationships between traffic flow variables play important roles in traffic engineering. They are used not only in basic traffic flow analyses but also in some macroscopic traffic flow simulation models. Various mathematical formulations that describe the relationships among density, flow, and speed have been proposed, including multi regime models. Previously, the best mathematical curve was determined by trying several different formulas and applying regression analysis. In these processes, one must specify in advance which mathematical formula should be adopted and where it should be shifted to another in a multiregime model. Neural network models have some promising abilities to represent nonlinear behaviors accurately and to self-organize automatically. A procedure for describing the macroscopic relationships among traffic flow variables using some neural network models is presented in [14]. Some neural network models, such as a multilayer model, have the promising ability to describe nonlinear behaviors very well. But, this method is required many experimental data and complex at implementation.

2.2. Description of the task solution method

Proposed mathematical model does not require many experimental data and enough simple at implementation. The essence of this model is that the experimental data, consisting of a number of daily observations of the traffic intensity at the intersection, are approximated by an analytical functional dependence in the form of a polynomial of the *n*-th degree $P_n(x)$

$$P_n(x)= f(x)=a_n x^n+a_{n-1}x^{n-1}+ a_{n-2}x^{n-2}+ \quad + a_{n-2}x^2+ a_1 x+ a_0, \qquad (2.3)$$

where *x* – variable; a_i, i=0, 1, ,*n*- constant numbers.

Usually experimental data that represent functional dependence $y= f(x)$ from the variable *x*, is obtained in a tabular way. In this case, in the table, for example, one of the columns is an independent variable (argument), and the other columns are functions of this argument.

Hereinafter, to simplify mathematical model let us assume that the degree of polynomial (2.3) should not exceed 3, i.e. $n \le 3$.

Obviously, the number of observations of the traffic intensity at the intersection should significantly exceed 4. In this regard, in order to obtain an analytical functional dependence $P_n(x)$ it is necessary to compose and solve a system of linear algebraic equations of the form

$$\begin{cases} y_1 = a_n x_1^n + a_{n-1} x_1^{n-1} + \cdots + a_{n-2} x_1^2 + a_1 x_1 + a_0; \\ \cdots\cdots\cdots\cdots\cdots\cdots \\ y_m = a_n x_m^n + a_{n-1} x_m^{n-1} + \cdots + a_{n-2} x_m^2 + a_1 x_m + a_0, \end{cases} \qquad (2.4)$$

m – number of observations, $m>4$ and $m>n$, y_i, $i=1,\dots,m$ - function value

$y=f(x)$ при $x=x_m$.

The solution of the system of linear equations (2.4), i.e. finding the coefficients a_i, $i=0,1,\dots,n$, can be carried out by the method of least squares (MLS) [17].

The least squares method is a mathematical method used to solve various problems, based on minimizing the sum of the squares of the deviations of some functions from the desired variables. It can be used to "solve" overdetermined systems of equations (when the number of equations exceeds the number of unknowns).

The essence of the least squares method. Let *x* — be a set of unknown variables (parameters), and $f_i(x)=y_i$, $i=1,\dots,m$— a set of functions from this set of variables. The task is to select such values so that the values of these functions are as close as possible to some values. In essence, we are talking about the "solution" of an overdetermined system of equations, in the indicated sense of the maximum proximity of the left and right sides of the system. The essence of the LSM is to choose the sum of the squares of the deviations of the left and right sides as a “measure of distances”. Thus, the LSM estimation criterion can be expressed as a functional:

$$J = \sum_i e_i = \sum_i (y_i - f_i(x))^2 \rightarrow \min . \qquad (2.5)$$

which minimizes the sum of the squares of the deviations i=1,…,m.

If (2.5) has a solution, then the smallest value of the sum of squares will be equal to zero, and exact solutions (2.5) can be found analytically or, for example, by various numerical optimization methods.

If the system is redefined, that is, the number of independent equations is greater than the number of sought variables, then the system does not have an exact solution and the least squares method allows finding some "optimal" vector in the sense of maximum approximation of vectors or maximum proximity of the vector of deviations to zero [17] (approximation understood in the sense of Euclidean distance).

To solve problems using LSM, special programs have been developed in the Mathlab, Python and so on programming environments.

However, for the application of these programs, a special presentation of the initial data is required, and the resulting solution is rigidly connected with the initial data included in the program. The proposed solution is free from such disadvantages.

Due to the peculiarity of our problem, it is advisable to introduce 2 independent variables, namely, the two phase change times t_1– is the time when the green signal is turned on at the traffic light, t_2 - is the time when the red signal is turned on at the traffic light. We will neglect the time when the yellow signal turns on at the traffic light. Then on each direction of the road $t_1 + t_2 = t$, where

t - is the current time.

In this case, the traffic intensity at the intersection will depend on 2 variables t_1 and t_2.

The next step in solving the problem is to determine the extrema of function (2.3) and function 2-th variables $z=z(x,y)$, where $x=t_1$, $y=t_2$.

It is known from math [16] about necessary conditions of local extreme for analytical function.

Let a function $y=f(x)$ be defined in a δ-neighborhood of a point x_0, where δ>0.

The function $f(x)$ is said to have a local (or relative) maximum at the point x_0, if for all points $x\neq x_0$ belonging to the neighborhood $(x_0-\delta, x_0+\delta)$ the following inequality holds:

$$f(x)\leq f(x_0).$$

If the strict inequality holds for all points $x\neq x_0$ in some neighborhood of x_0:

$$f(x)<f(x_0),$$

then the point x_0 is a strict local maximum point.

Similarly, we define a local (or relative) minimum of the function $f(x)$. In this case, the following inequality is valid for all points $x\neq x_0$ of the δ-neighborhood of the point x_0:

$$f(x)\geq f(x_0).$$

Accordingly, a strict local minimum is described by the inequality

$$f(x)>f(x_0).$$

The concepts of local maximum and local minimum are united under the general term local extremum. The word “local” is often omitted for brevity, so it is said simply about maxima and minima of functions.

A necessary condition for an extremum is formulated as follows:

If the point x_0 is an extremum point of the function $f(x)$, then the derivative at this point either is zero or does not exist. In other words, the extrema of a function are contained among its critical points.

Note that the necessary condition does not guarantee the existence of an extremum.

Local extrema of differentiable functions exist when the sufficient conditions are satisfied. These conditions are based on the use of the first-, second-, or higher-order derivative. Respectively, 3 sufficient conditions for local extrema are considered. Local extrema of differentiable functions exist when the sufficient conditions are satisfied. These conditions are based on the use of the first-, second-, or higher-order derivative.

Respectively, 3 sufficient conditions for local extrema are considered. But proof this formulation we omit here.

Hereinafter, we’ll guide by next rule:

Let the first derivative of a function $f(x)$ at the point x0 be equal to zero:

$f'(x_0)=0$, that is x_0 is a stationary point of $f(x)$. Suppose also that there exists the second derivative $f''(x_0)$ at this point. Then

- If $f''(x_0)>0$, then x_0 is a strict minimum point of the function $f(x)$;
- If $f''(x_0)<0$, then x_0 is a strict maximum point of the function $f(x)$.

The optimal value of function (2.3) found in this way can be used to construct work algorithm of the automatic traffic control system at the intersection.

The adaptive algorithm of traffic lights functioning directly at the intersection must also use feedback on the magnitude of the difference in q_i values on the intersecting directions of traffic.

A necessary criterion for the extremum of a function of two variables. If the point $P(x0, y0)$ - is the extremum point of a function of two variables $z = z(x, y)$, then the first partial derivatives of the function (with respect to "x" and "y") at this point are equal to zero or do not exist:

To determine the optimal mode of functioning of traffic lights at intersections, it is advisable to perform the following operations:

1) point 2 of the algorithm: collect information about Intensity movement, Temporal interval and other characteristics of vehicle movement at a given intersection, depending on the time of day;

2) point 3,4: present the collected information in the form of tables and, then, in the program for working with spreadsheets, Microsoft Office Excel, present the collected information in the form of functional dependencies, for example, the dependence of the number of vehicles at an intersection on the time of day.

Obviously, the resulting dependence will have a complex, non-linear nature, which cannot be presented in an analytical form. In addition, the collected information is only a single implementation of a random process, which can be described by some random functions. At the same time, the obtained practical implementation can be investigated using the methods of mathematical analysis;

3) point 5-7: to simplify the study of the obtained dependence, we represent it in the form of a polynomial of a given degree. Microsoft Office Excel provides a function for representing a trend graph function as a polynomial of a given degree. In this case, the trend line is built using the least squares method.

This trend line provides a specified number of points that define the relationship between an independent variable, such as time of day, and a dependent variable (function), such as the number of vehicles at an intersection;

4) point 8,9: by the selected points, a system of linear algebraic equations is compiled, by solving which it is possible to obtain the coefficients of a polynomial of a given degree and, accordingly, the desired functional dependencies in an explicit form;

5) point 10: the obtained functional dependence using the differentiation operation can be investigated for the presence of extreme (optimal) values in it, which should be used in the work of an adaptive traffic light.

3.1. Construction of a power polynomial from given input data

Very often, the coefficients of the equations (2.4) are real or complex numbers and the solutions are searched in the same set of numbers, but the theory and the algorithms apply for coefficients and solutions in any field.

For solving systems of algebraic linear equations, in which the number of equations is equal to the number of unknown variables and which have a unique solution. more often than others, two methods are used:

- solving linear algebraic equations by Cramer's method (using determinants for systems of any order);

- Gauss method (method of successive elimination of unknown variables, usually for low-order systems).

In this work, we use Cramer's method. The essence of Cramer's method is as follows.

Suppose we need to solve a system of linear algebraic equations

$$\begin{cases} a_{11}x_1 + a_{12}x_2 + \ldots + a_{1n}x_n = b_1; \\ a_{21}x_1 + a_{22}x_2 + \ldots + a_{2n}x_n = b_2; \\ \vdots \\ a_{n1}x_1 + a_{n2}x_2 + \ldots + a_{nn}x_n = b_n \ , \end{cases} \qquad (3.1)$$

in which the number of equations is equal to the number of unknown variables and the determinant of the main matrix of the system is nonzero, that is,
det(A) №0.

Let be D -- determinant of the main matrix of the system, and $D_{x_1}, D_{x_1}, \ldots, D_{x_n}$ -- determinants of matrices that are obtained from *A* by replacing the 1-*st*, 2-*nd, …, n-th* columns, respectively, with the column of free terms:

$$D = \begin{vmatrix} a_{11}a_{12}\ldots a_{1n} \\ a_{21}a_{22}\ldots a_{2n} \\ . \\ \text{Ч} \\ a_{n1}a_{n2}\ldots a_{nn} \end{vmatrix}, \quad D_{x_1} = \begin{vmatrix} b_1a_{12}\ldots a_{1n} \\ b_2a_{22}\ldots a_{2n} \\ . \\ \text{Ч} \\ b_na_{n2}\ldots a_{nn} \end{vmatrix},$$

$$D_{x_2} = \begin{vmatrix} a_{11}b_1\ldots a_{1n} \\ a_{21}b_2\ldots a_{2n} \\ . \\ \text{Ч} \\ a_{n1}b_n\ldots a_{nn} \end{vmatrix}, \quad D_{x_n} = \begin{vmatrix} a_{11}a_{12}\ldots b_1 \\ a_{21}a_{22}\ldots b_2 \\ . \\ \text{Ч} \\ a_{n1}a_{n2}\ldots b_n \end{vmatrix}.$$

With this notation, the unknown variables are calculated by the formulas of Cramer's method as $x_1 = D_{x_1}/D,\ x_2 = D_{x_2}/D, \ldots, x_n = D_{x_n}/D$.

This is how the solution of a system of linear algebraic equations is found by Cramer's method. When applying Cramer's method to our problem, i.e. to the solution of system (2.4), it is necessary to use the y_i column instead of the $в_i$ column, and instead of the coefficients a_{ij} - the quantities x_i^j .

3.2. The manner of optimal values finding

The algorithm of optimal values finding for a function of one variable consists in the following sequence of actions:

- first, find the 1st derivative of the polynomial (2.3) and, after equating the resulting derivative to zero, a list of singular points is determined;

- then find the second derivative of the polynomial (2.3) and find the optimal solution to the problem.

The algorithm of optimal values finding for a function of two variables consists in the following sequence of actions:

- first, find the 1st derivatives of the function $z=z(x,y)$ by variables x and y;
- then equate 1st derivatives of the function $z=z(x,y)$ to zero.

movement and the number of lanes used;

- hourly intensity and composition of traffic in directions;
- traffic delays in directions;
- availability of technical means of regulation: traffic light, priority signs, prohibition and prescriptive signs;
- geometric parameters of the intersection (Fig. 4.2).

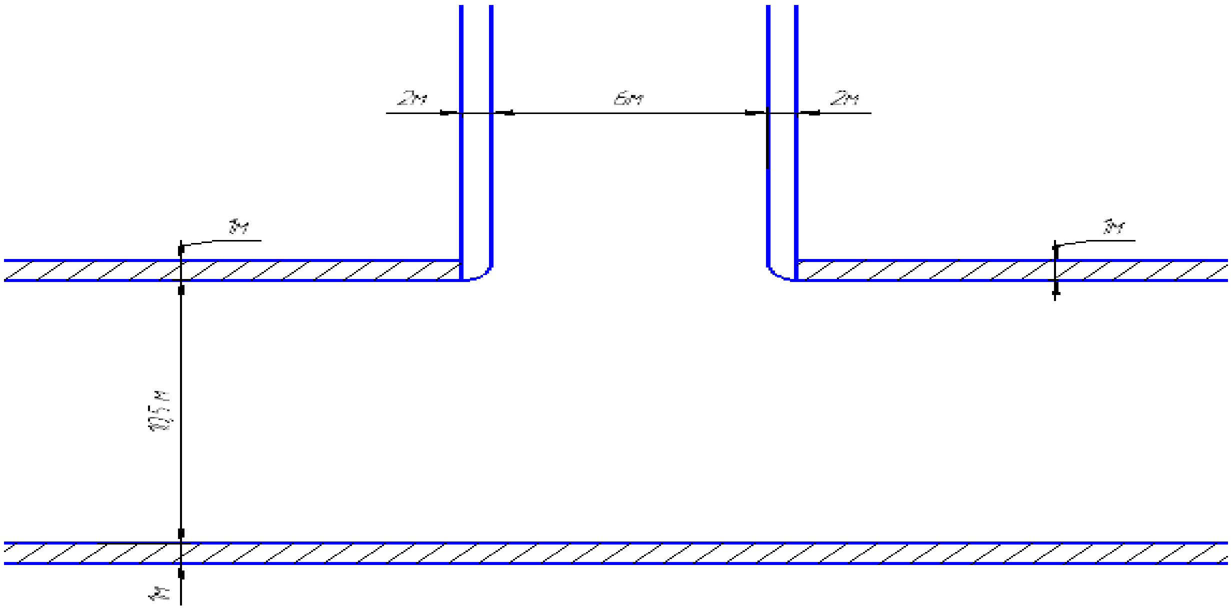


Fig. 4.2. Geometric dimensions of the intersection

Composition of the traffic flow in all directions is presented in Table 4.1.

Tab. 4.1

Composition of the traffic flow in all directions

Vehicle type	Share in the stream,%	Traffic intensity of vehicles/hour
cars	97,31	2100
buses	2,6	56
trucks	0,09	2

As follows from this data main stream of vehicles on intersect are cars.

It is known [18] that the average length of the car S_a is approximately 4.5 m.

Usually the average interval between cars near intersect *S* averages 3 m that is the dynamic vehicle dimension (see Fig. 1.6)

$$D\text{=S+ }S_a\text{ =7.5(m).} \tag{4.1}$$

If we know the number of cars between detectors D1 and D2, before intersect, that it is easy to estimate a length traffic jam. Comparing a length of the traffic jam on all lanes of the intersection, one can go from the previously adopted discrete criterion (composed of the number of cars) to a continuous criterion - the length of the traffic jam.

In Table 4.2 is shown measured values of time delay at traffic lights in direction *N2* and average speed of traffic at an intersection in the same direction.

Tab. 4.2

Time delays at traffic lights in direction *N2* and average vehicle speed at an intersection (see Fig. 4.1)

t_{day}, .hour	Δ*t*.sec	*Vcr*, km/hour
8:10	40	15
10:30	60	17
17:50	60	20
19:40	30	18
21:05	60	24
9:40	40	20
12:25	50	25
16:00	60	19
20:20	30	21
18:30	40	21
19:03	50	23
19:21	40	19
11:00	60	20

8:50	40	18
10:59	50	20
15:16	30	23
16:40	60	19
19:49	40	20
22:00	60	22

The dependence of transport delays Δ*t* in the direction of movement of the *N*2 on the time of day is shown in Fig. 4.3. In the case of approximating a real curve, i.e. adding a trend line in the form of a polynomial of the 4th degree, we obtain the functional dependence shown in Fig. 4.4.

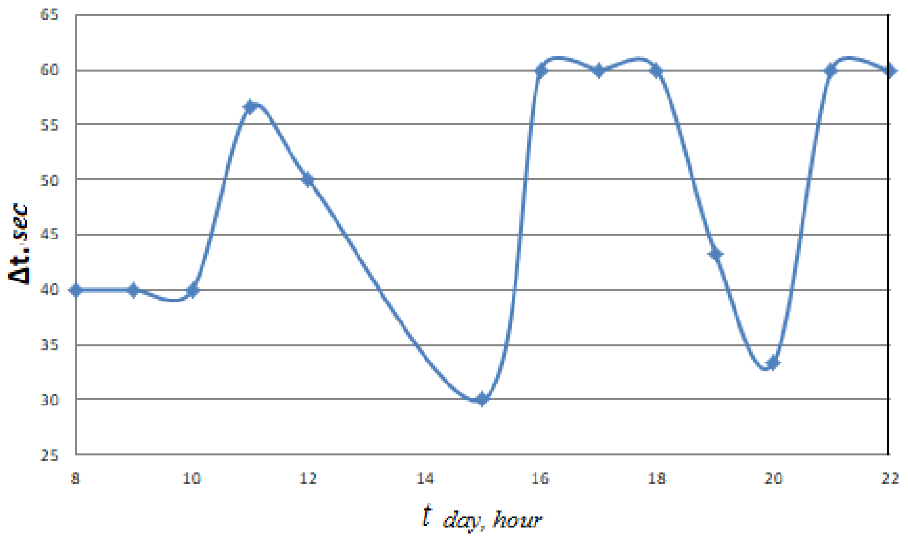


Fig. 4.3. Dependence of Δ*t* on the time of day

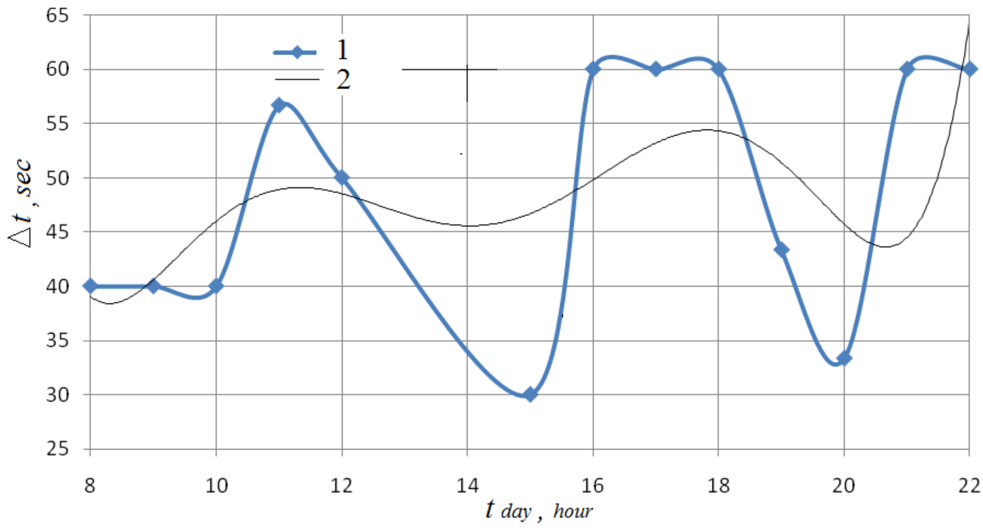


Fig. 4.4. Dependence of Δ*t* on the time of day (1) and its trend line (2)

The dependence of the average speed V_{cr} of passing the intersection is shown in Fig. 4.5.

When adding trend lines in the form of polynomials of the 4th and 5th degrees, we obtain the functional dependencies shown in Fig. 4.6.

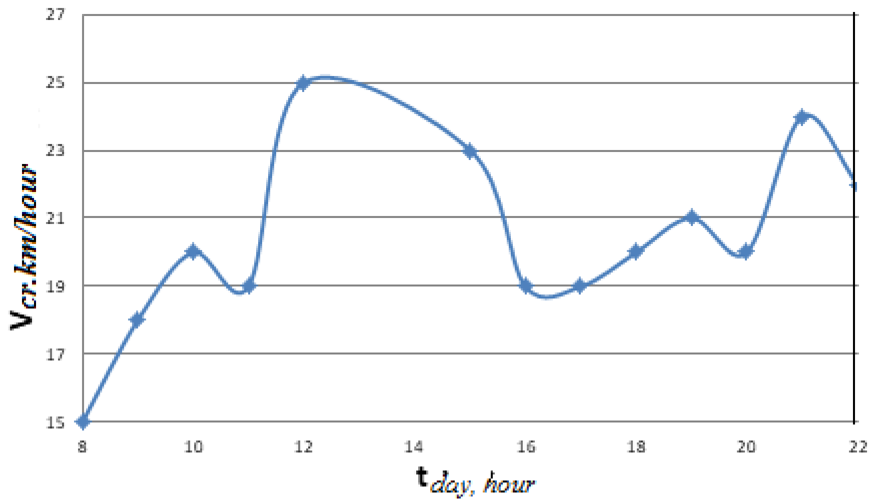


Fig. 4.5. Dependence of V_{cr} on the time of day

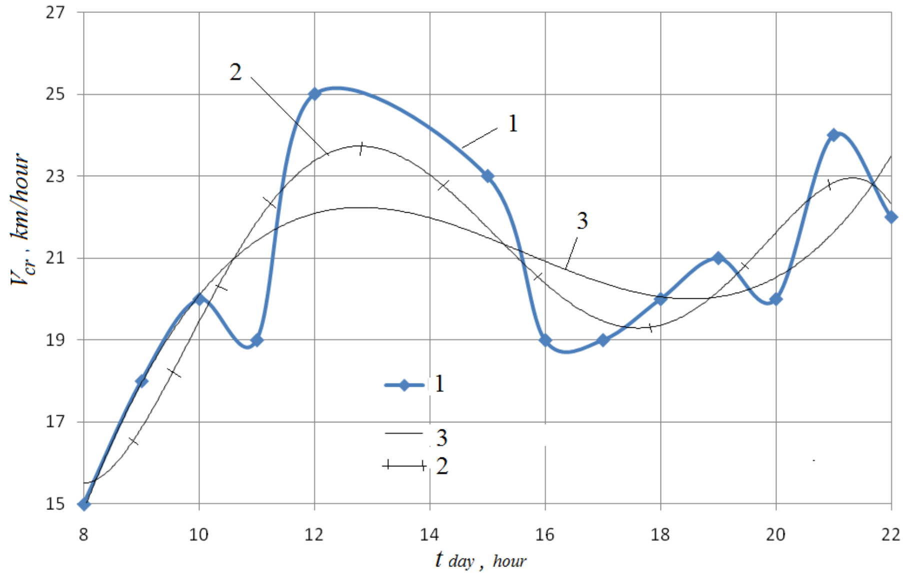


Fig. 4.6. Dependence of V_{cr} on the time of day and its trend lines:

1- Real curve; 2- polynomial 5-th power; 3- polynomial 4-th power.

As can be seen from Fig. 4.6 polynomial 5-th power better approximates the dependence $V_{cr}=f(t)$, then polynomial 4-th power.

Consequently, it is difficult to approximate the real dependences of the traffic parameters with a low degree polynomial. In this regard, it is advisable to divide the daily traffic schedule of road transport into certain stages, for example, 1) from 8 to 11 o'clock; 2) from 11 am to 4 pm; 3) from 16 to 20 hours.

In this case, the measurements of road traffic at each of the stages can be approximated with a sufficiently high accuracy by a polynomial of the 3rd degree.

As an example, we will approximate the experimental curve in the time interval from 8 to 11 hours by a polynomial of the second degree, i.e. construct a polynomial P_2(t) gj by 3 points given in Table. 4.3.

Table. 4.3.

t, hour	8	9	10	11
V_{cr}, km/hour	15	18	20	19
V_{cr},	4.17	5	5.56	

m/s	5.28

Based on the data in Table. 4.3. one can write the following equations

$$\begin{cases} 15 = a_2\ 64 + a_1 8 + a_0; \\ 18 = a_2\ 81 + a_1 9 + a_0; \\ 20 = a_2\ 100 + a_1 10 + a_0, \end{cases} \qquad (4.2)$$

whose unknown coefficients are determined using Cramer's method. For this purpose, the determinants of system (4.2) of the form are compiled and calculated

$$D = \begin{vmatrix} 64 & 8 & 1 \\ 81 & 9 & 1 \\ 100 & 10 & 1 \end{vmatrix}, \quad D_{a_2} = \begin{vmatrix} 15 & 8 & 1 \\ 18 & 9 & 1 \\ 20 & 10 & 1 \end{vmatrix},$$

$$D_{a_1} = \begin{vmatrix} 64 & 15 & 1 \\ 81 & 18 & 1 \\ 100 & 20 & 1 \end{vmatrix}, \quad D_{a_0} = \begin{vmatrix} 64 & 8 & 15 \\ 81 & 9 & 18 \\ 100 & 10 & 20 \end{vmatrix}.$$

Calculating the values of the determinants $\Delta = -2; \Delta_{a_2} = 1; \Delta_{a_1} = -23; \Delta_{a0} = 90,$ a polynomial of the 2nd degree of the form

$$P(\mathrm{t}) = V_{cr}(t) = -0.5t^2 + 11.5t - 45,$$

where t – time in hours.

4.2. Calculation of the optimal automatic traffic control system

For the calculation of the optimal automatic traffic control system, the initial data given in [12, 15] are used. So, for example, according to [12], the maximum traffic intensity will be N =16941 auto / h (see Fig. 2.1) or $N_{П}$ = 2118 auto / h per lane. These data approximately coincide with similar values at a number of intersections in Kiev.

When constructing a polynomial of the 3rd degree, it is necessary to have 4 points from the graph of the experimental data. For this purpose, we will use the experimental data given in [15] (see Fig. 1.2) which characterize the intensity of traffic at the intersection in question.

According to the given data, the traffic intensity at the intersection under consideration can be characterized by the values that are given in Table. 4.3.

According to (2.1) queues of horizontal and vertical roads, respectively are l_1 and l_2.

However, instead of the values l_1 and l_2 it is more convenient to consider traffic intensities of horizontal and vertical roads q_1 and q_2.

To use the apparatus for determining the extrema of continuously differentiable functions of 2 variables, we will move from the values of the traffic intensity of horizontal and vertical roads q_1 and q_2 to the values of the length of the traffic flow on the horizontal and vertical roads S_1 and S_2, and are written in the form S_1=7.5 q_1, S_2=7.5 q_2.

Change in the total length of the traffic flow on vertical road S_v for n cycles can write in type

$$S_v=7.5\, q_1 t_2 n,$$

and the total length of the traffic flow on horizontal road

$$S_{h=}7.5\ q_2 t_1 n.$$

With a permitting traffic light signal, the total length of the flow of vehicles on the vertical road for n cycles will decrease by

$$S_{vп}= 2V_1 t_1 n,$$

and the total length of the traffic flow on horizontal road will decrease by

$$S_{hп}= 2V_2 t_2 n.$$

Thus, the dependence of the length of the traffic flow at the intersection on time can be written in the form

$$S_s= 7.5\ q_1 t_2 n- 2V_1 t_1 n+7.5\ q_2 t_1 n-2V_2 t_2 n. \qquad (4.3)$$

Let us assume that the traffic flow rates at the intersection have functional time dependences of the form $V_1=a_1 t_1$ and $V_2=a_2 t_2$, and the quantities q_1 and q_2 are constant.

In this case the value S_s can write

$$S_s= 7.5\ q_1 t_2 n-2a_1 t_1^2\ n+7.5\ q_2 t_1 n-2a_2 t_2^2 n. \qquad (4.4)$$

Let us find the partial derivatives of the function S_s with respect to t_1 and t_2:

$$\partial S_s / \partial t_1 = -4a_1t_1n + 7.5q_2n, \;\; \partial S_s / \partial t_2 = -4a_1t_2n + 7.5q_1n, \quad (4.5)$$

and equate them to zero.

From the obtained equations, two relations follow, which relate the time values of the phases of traffic light switching with the traffic intensity at the intersection under consideration

$$t_1 = \frac{7.5q_2}{4a_1},$$

and

$$t_2 = \frac{7.5q_1}{4a_2}.$$

However, the obtained values of t_1 and t_2 are not extreme points of function (4.3).

Obviously, for a larger value of *q* on one of the directions of the intersection, the allowed interval of movement for this direction at the intersection under consideration should also be greater. At the same time, the average speed of the traffic flow at the intersection of the intersection, for this direction, must also exceed the average speed of the traffic flow in the cross direction. Since it is assumed that at a prohibiting traffic light, the traffic flow in front of the traffic light stops, i.e. has V=0, then each of the cars accelerates to a certain speed $V= V_{cr}$.

Let the quantity q_1=bt=$b(t_1+t_2)$, and the quantity $q_2 = ct < q_1$.

Let us also assume that the average speed of the traffic flow with the q_1 value is equal to V_1, and the average speed of the traffic flow in the cross direction is V_2.

Substituting these quantities into (4.3) and differentiating the function S_s with respect to t_1 and t_2, we obtain

$$\partial S_s / \partial t_1 = 7.5b2t_2n - V_1n + 7.5c2t_1n + 7.5ct_2n; \quad (4.6)$$

$$\partial S_s / \partial t_2 = 7.5bt_1n + 7.5b2t_2n + 7.5ct_1n - V_2n. \quad (4.7)$$

Once again differentiating the functions with respect $\partial S_s / \partial t_1$ and $\partial S_s / \partial t_2$ to t_1 and t_2, we obtain

A= $\partial^2 S_s / \partial t_1^2 = 15cn;$ B= $\partial^2 S_s / \partial t_2^2 = 15bn;$ C= $\partial^2 S_s / \partial t_1 \partial t_2 = 7.5bn + 7.5cn.$

According to a sufficient criterion for the existence of an extremum, there should be Δ>0, where

$$D = \begin{vmatrix} A & B \\ B & C \end{vmatrix} = AC - B^2.$$

In this way,

$$\Delta = 15cn7.5(b+c)n - 225b^2n^2. \quad (4.8)$$

From (4.8) follows the condition for a sufficient criterion for the existence of an extremum

$$c(b+c) > 2b^2.$$

For further calculations, we will use the dependence of *q* from time (Fig. 4.7).

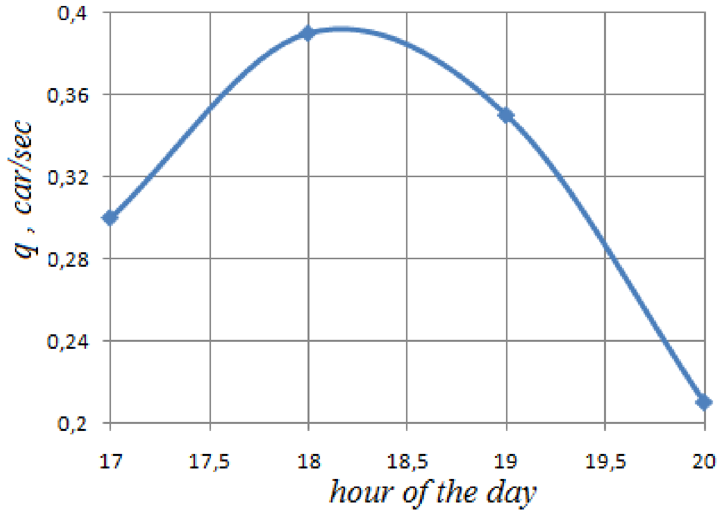


Fig. 4.7. Dependence of *q* from time

Equating equations (4.6) and (4.7) to zero and solving them together, namely, dividing the 1st equation by the 2nd and denoting the ratio t_1/t_2=γ, we define the singular point of the function S_s -γ =3.33.

Since $t_1+t_2 = t$, the phase ratio of traffic signals for the case under consideration should be 23% and 77%.

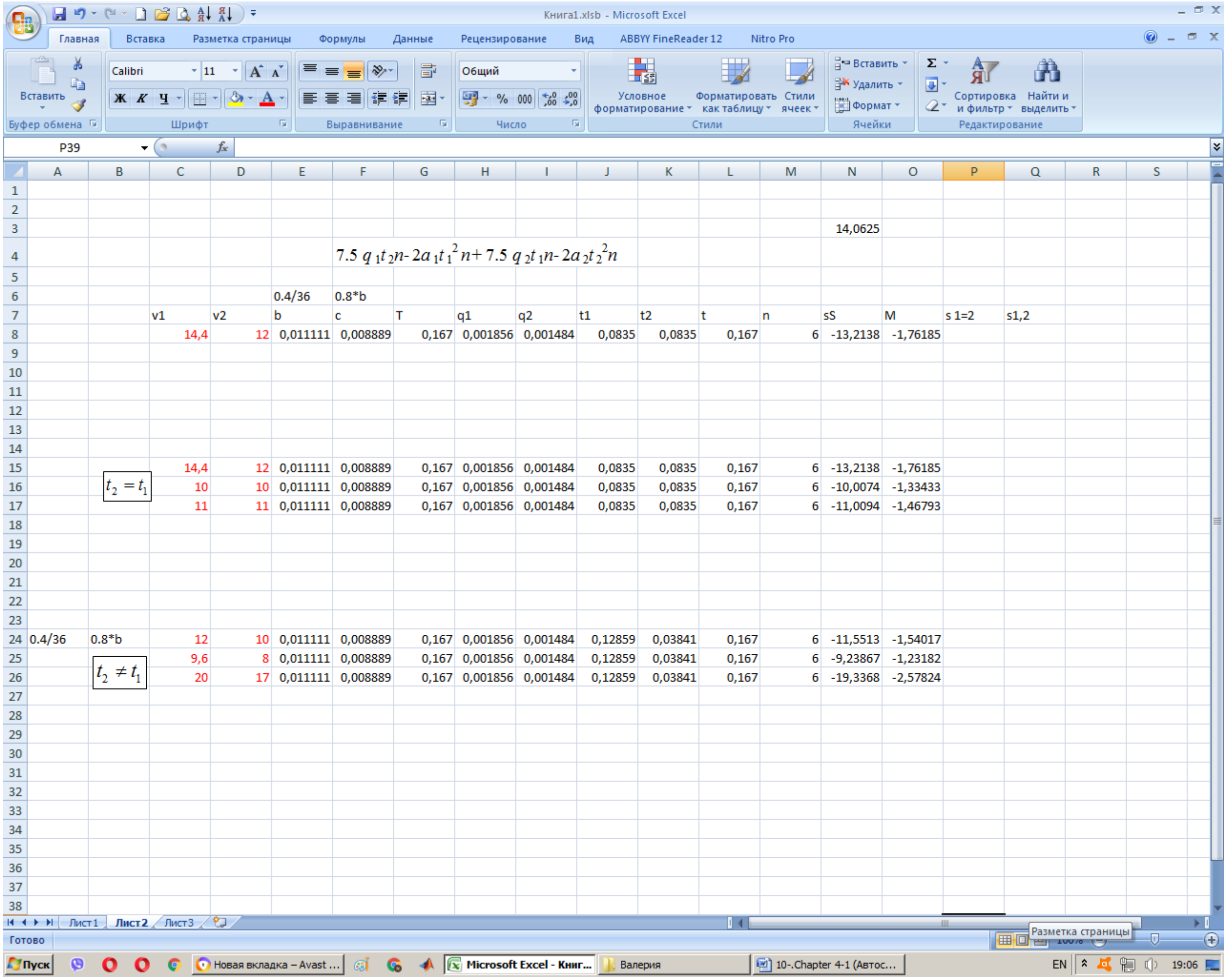
The calculations show that when considering a 10-minute interval of traffic light operation with such a phase ratio of its signals, it is possible to obtain up to 50% increase in traffic through the intersection (Table 4.4), depending on the ratio of the speeds of intersecting traffic flows.

Tab. 4.4. Passage of vehicles through an intersection depending on the ratio of the speeds of intersecting traffic flows

	V_1, m/s	V_2, m/s	ΔS_s, %
$t_2 \neq t_1$	9,6	8	47,78-
	12	10	59,74
	20	17	100
$t_2 = t_1$			
	10	10	51,75

The calculations also show that the traffic flow through the intersection significantly depends on the values of the speeds of the intersecting traffic flows.

The calculations were carried out in Excel. Print-screen of one of the calculations is shown in Fig. 4.8.



$$7.5\,q_1 t_2 n - 2a_1 t_1^2 n + 7.5\,q_2 t_1 n - 2a_2 t_2^2 n$$

Row	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
3														14,0625			
6					0.4/36	0.8*b											
7			v1	v2	b	c	T	q1	q2	t1	t2	t	n	sS	M	s 1=2	s1,2
8			14,4	12	0,011111	0,008889	0,167	0,001856	0,001484	0,0835	0,0835	0,167	6	-13,2138	-1,76185		
15			14,4	12	0,011111	0,008889	0,167	0,001856	0,001484	0,0835	0,0835	0,167	6	-13,2138	-1,76185		
16		$t_2 = t_1$	10	10	0,011111	0,008889	0,167	0,001856	0,001484	0,0835	0,0835	0,167	6	-10,0074	-1,33433		
17			11	11	0,011111	0,008889	0,167	0,001856	0,001484	0,0835	0,0835	0,167	6	-11,0094	-1,46793		
24	0.4/36	0.8*b	12	10	0,011111	0,008889	0,167	0,001856	0,001484	0,12859	0,03841	0,167	6	-11,5513	-1,54017		
25			9,6	8	0,011111	0,008889	0,167	0,001856	0,001484	0,12859	0,03841	0,167	6	-9,23867	-1,23182		
26		$t_2 \neq t_1$	20	17	0,011111	0,008889	0,167	0,001856	0,001484	0,12859	0,03841	0,167	6	-19,3368	-2,57824		

Fig. 4.8. Print-screen for calculating the total traffic flow at the intersection

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CONCLUSIONS

One of the bottlenecks in the urban transport network, which interfere with road traffic without stopping traffic, are intersections.

Traffic lights with a fixed mode of operation at intersections do not take into account the uneven congestion of intersecting roads.

Taking into account such unevenness allows for adaptive traffic lights.

Development of the algorithms for the automatic traffic control system at the intersection is the theme of this work.

When performing the work, a review and analysis of existing methods of developing algorithms for the operation of adaptive traffic lights was carried out.

After analyzing the existing methods, a simple approximate way of developing an algorithm for the operation of an adaptive traffic light, taking into account the traffic intensity and the speed of transport on intersecting roads, is proposed.

In particular, it is shown that the phases of the traffic light cycle for a given direction of the road should be proportional to the value of its traffic load.

Calculations are presented that show the effectiveness of the proposed algorithm.