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FEATURES OF THE APPLICATION OF TRAFFIC FLOW MANAGEMENT METHODS AND TOOLS

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Abstract: **This article examines the causes and consequences of traffic jams, describes typical traffic flow behavior and analyzes traffic control methods and means. The paper demonstrates the proposed classification of traffic lights by type of regulation. In summary, the article represents a detailed overview of existing cyber-physical traffic control systems, such as SEA TCS, InSync and MASSTR. The article analyzes the existing methods of traffic regulation, examines the causes and consequences of congestion, the division of intersections into regulated and unregulated, and the classification of traffic lights by type of traffic control. Among the main parameters of traffic flow used by cyber-physical traffic control systems, the primary and most used are speed, density, and volume of vehicles. The article also reviews the existing cyber-physical traffic control systems and the primary technologies.**

Index Terms: **Traffic, congestion, intersection, traffic light controller, adaptive traffic control, cyber-physical system.**

I. INTRODUCTION

Transport is an integral part of the modern world without which technical and social progress would be impossible [1]. The main task of transport is to fully and timely meet the needs of the national economy and population in transportation and accelerate the delivery of goods and movement of passengers based on a significant increase in capacity and quality of the entire transport system [13].

The number of cars on the roads around the world is growing every year [3]. In Ukraine, the annual growth of the car fleet is about 10%. The rapid increase in the number of fleets is accompanied by an increase in the number of victims of road accidents. If before the beginning of the XX century, there were about six thousand cars in the world [4], now the world's car fleet has more than 520 million units (of which about 75% - are cars).

II. LITERATURE REVIEW AND PROBLEM STATEMENT

The increase in traffic and demand for transport has caused serious congestion [5], delays [6], accidents, and environmental problems [7], especially in large cities. Congestion has become a real scourge that plagues both industrialized and developing countries [8]. This affects both motorists and public transport users and also has a negative consequence for society - reduced economic efficiency [9].

Many people have already started research in areas of Intelligent Transport Systems [10]and smart traffic lights [11] to address these issues. Those researches include machine learning and deep learning [12], genetic algorithm [13], fuzzy logic [14], blockchain [15] and neural network applications [16].

Bo Liu and Zhentao Ding proposed a distributed deep reinforcement learning algorithm for the traffic light control problem, which consists of local learning and global consensus [12]. In their study, centralized learning is substituted by distributed learning agents which learn from their neighbors` experience data samples.

Genetic algorithm application for optimizing traffic signal timing was proposed by Dinh Tuan Hai, Do Van Manh, and Nguen Minh Nhat [13]. In their paper, a generic algorithm emission-based model [11] was proposed to generate a comprehensive performance index to present an optimal traffic signal timing scheme. Their model showed a significant performance increase for data collected from a single intersection.

Another algorithmic approach to solving the congestion problem is suggested by Abdou A. A., Farrag H. M., and A. S. Tolba in a paper called "A Fuzzy Logic-Based Smart Traffic Management Systems" [14]. These researchers introduced a system to control road traffic based on the density and rain condition information using fuzzy logic techniques to get the perfect time for every junction. It opens roads based on density in sequential order and also gives more time for each road based on rain conditions.

Multi-Agent autonomous intersection management (MA-AIM) system leveraging both EoT and blockchain [15] technologies was described by Buzachis A., Celesti A., Galleta A., Fazio M., Fortino G., Villari M. This system combines vehicle-to-vehicle with infrastructure-to-vehicle communications and has focus on security.

III. SCOPE OF WORK AND OBJECTIVES

The purpose of this article is to examine the causes and consequences of congestion, review the methodology of calculation traffic flow parameters, analyze various tools and methods to describe different approaches to solve the problem of congestion and delays, and give a classification of traffic lights based on the type of regulation. Based on the classification, choose an approach that will help to reduce delays and decrease the number of emissions from burning fuel by cars in a typical millionaire city. Develop an experimental system that will implement an Ant colony optimization algorithm and compare results with other centralized traffic control systems. Demonstrate the developed experimental system using the Ant Colony Optimization (ACO) algorithm that increases the system's availability and resilience by applying multiple local mini-servers instead of a single remote cluster and has the potential to reduce traffic delays by up to 10% and more.

IV. METHODS AND MEANS OF TRAFFIC REGULATION

Congestions are divided into two categories: periodic and non-periodic. About half of all congestions are intermittent and occur due to insufficient traffic capacity. Non-periodic congestion can be described as temporary interruptions - bad weather or traffic accidents. The causes of congestion can be divided into four specific categories:

1) Weather conditions (non-periodic).
2) Mechanical faults (non-periodic).
3) Human factor (non-periodic).
4) Infrastructure (periodic).

The most common place of congestion in the city is the intersection. The intersection is a key hub of urban traffic and, depending on the categories of intersecting streets is divided into unregulated, ring traffic, and regulated.

A regulated intersection is an intersection where the order of travel is regulated by signals of a traffic light or a regulator. The scheme of the regulated intersection is shown in Fig. 1. [16], where numbers from 0 to 11 correspond to a separate traffic lane and permitted directions of movement are indicated by arrows.

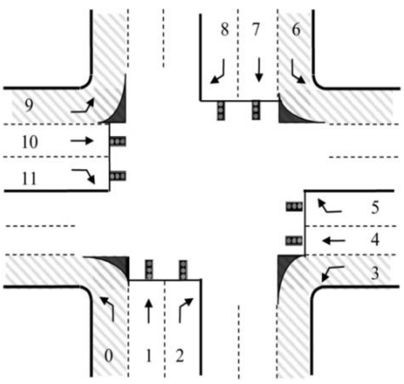

Fig. 1. Scheme of regulated intersection

The operation of traffic lights at regulated intersections directly affects the traffic flow passing through the intersection for a certain period of time (intersection capacity). The capacity of one lane at the intersection is determined at the speed of traffic at the intersection V = 30 km / h according to the formula:

$$P = \frac{3600\left(t - \frac{V}{26a}\right)}{t * T}, \quad (1)$$

where t - duration of the green phase of traffic lights; T - the duration of the traffic light.

There is a separate traffic light for all common types of vehicles. According to the purpose of traffic lights for certain vehicles are divided into three categories:

- road and street.
- railway.
- river.

According to the types of traffic light regulation, traffic light controllers are divided into two categories:

- traffic light controller with constant regulation.
- traffic light controller with adaptive regulation.

The constant traffic light works in the same mode of operation regardless of the day of the week, traffic, and time of day. Such a traffic light is not sensitive to constant changes in the road situation (a combination of factors such as road conditions, the presence of obstacles on a particular section of road, intensity, and level of traffic organization) at the intersection. Thus, all vehicles in all sections of traffic have a fixed time to cross regulated intersections and the same priority for traffic in the road network. Mentioned traffic flow increases the delay time of vehicles at intersections and the creation of congestion. The delay time is characterized by the number of vehicles entering and leaving the intersection during the measurement period.

Based on previous works which served base for this article the scheme of traffic light controller classification is prepared and shown in Fig. 2. According to this scheme, the most effective method to address the problem of congestion and delays is the usage of cyber-physical systems for traffic flow regulation combined with various road detectors, traffic light controllers with dynamic network adaptive regulation mode and implementation of different algorithms (genetic/blockchain/fuzzy logic). Taking into account the selected methods, an experimental model will be developed using an ant colony optimization algorithm.

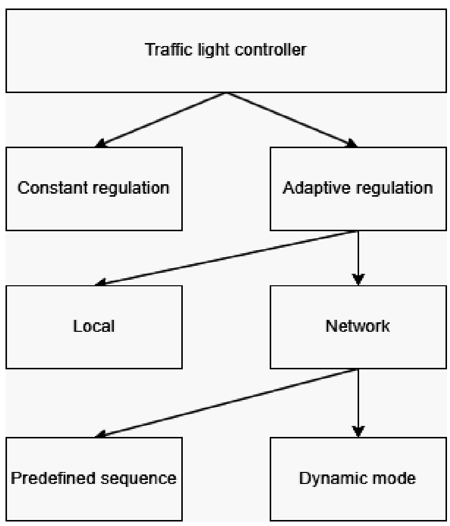

Fig. 2. Classification of traffic lights controllers

The adaptive traffic light changes the mode of operation to more effectively organize traffic, taking into account changes in the traffic situation. Adaptive control is designed to optimize the operation of traffic lights in order not to give a green signal in a direction where no one is, as well as more efficiently distributing the flow of cars. Since the mode of operation of traffic lights directly affects the bandwidth of the intersection, adaptive control can increase this parameter.

Adaptive control can be divided into local and network. In the local adaptive mode, the intersection is controlled by the readings of car detectors and adjustment is performed regardless of the condition of neighboring intersections. In the network adaptive mode, data is exchanged between adjacent intersections, due to which the management is coordinated and provides greater efficiency. Network adaptive modes, in turn, are divided into two types:

- a choice of predefined control sequences.
- dynamic mode.

Cyber-physical systems that implement dynamic adaptive modes are the most complex and expensive because they require a large number of transport detectors (input and output for each intersection), as well as complex programming and debugging. Such systems in real-time estimate the intensity of traffic, throughput, and distribution of traffic flow in the directions of movement while choosing the optimal mode of operation of traffic lights.

Dynamic adaptive mode is most often used in areas with a high density of intersections. Dynamic systems also allow to implement of the principle of the green wave.

Green wave - a mode of the traffic light, during which the green light is on the whole street, which allows vehicles to pass the segment as quickly as possible, instead of going from intersection to intersection, waiting for their turn at the traffic light. An example of a road on which a green wave is used is shown in Fig. 3 [17].

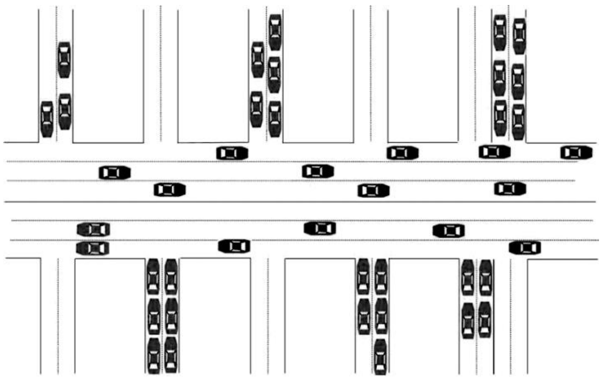

Fig. 3. The road with the Green Wave mode is applied

Cyber-physical systems that use adaptive traffic lights to improve traffic management are called automated traffic control systems. In general, automated traffic control systems can be represented as a set of road telematics devices, controllers, and automated workstations included in the data exchange network, with the organization of central and local control centers - depending on the density and intensity of traffic.

The structure of an automated traffic control system has a hierarchical form. Such a hierarchical structure contains a city control center, different high-level zone controllers, mid-level road controllers, and low-level traffic light controllers. Traffic light controllers are connected with controlled road signs as well as with different types of transport detectors. An example of structure is shown in Fig 4.

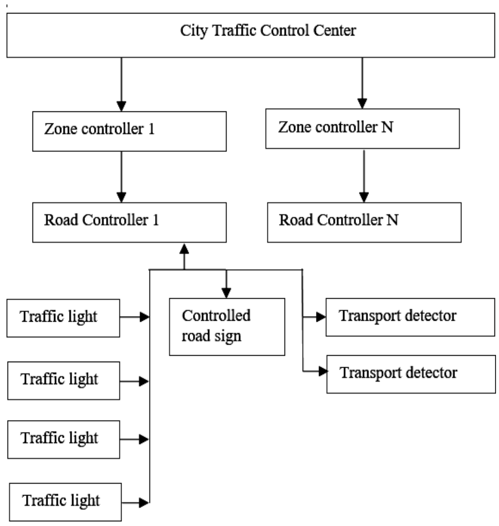

Fig 4. The structure of the automated traffic control system

The development of the modern hierarchical structure of automated traffic control systems was gradual - from the lower level of local manual control to computerized zonal and centralized systems, so the composition, architecture, functionality, and method of reprogramming on the road today use automated traffic control systems of several generations, which are divided into four levels. Calculation of control parameters and their input to road controllers[1]:

- The first generation - the calculation of control parameters and their input to the road controllers and later to the zonal controller`s traffic control systems, is performed manually.
- Second generation - the calculation of control parameters is automated on the computers of zonal controllers, but their input to the road controllers is done manually.
- Third generation - the calculation of control parameters and their input to the controllers of automated traffic control systems is automated. It is also possible to implement control with the forecast of the dynamics of traffic flows.
- Fourth generation - real-time automatic traffic control, when transport detectors collect information on controllers and adaptive control programs switch traffic lights at intersections, depending on the actual state of traffic and pedestrian flows.

V. METHODOLOGY OF CALCULATING TRAFFIC FLOW PARAMETERS

Traffic flow is a set of vehicles that simultaneously participate in traffic on a certain section of the road network. With the development of methods and equipment for the study of traffic flows, the range of indicators are used in the organization of traffic continues to expand. The most necessary and frequently used are:

1) Speed

Speed is seen as an indicator of the quality of travel, when drivers and passengers are more concerned about the speed of travel, than about the design aspects of traffic. It is defined as the speed of movement over a distance per unit of time. Mathematically it is presented as:

$$v = \frac{d}{t}, \quad (2)$$

where *v* is the speed of the vehicle in *m / s*, *d* is the distance traveled in *m* in time *t* seconds. The speeds of different vehicles will vary in time and space. There are several types of velocity to represent these differences. The most important of these are point speed, travel speed, average speed over time, and average speed in space.

2) Density

Density is defined as the number of vehicles occupying a given length of highway or lane and is usually expressed as vehicles per km. Mathematically it is presented as:

$$k = \frac{n_x}{x}, \quad (3)$$

where *x* is the length of the road, n_x is the number of cars on the road.

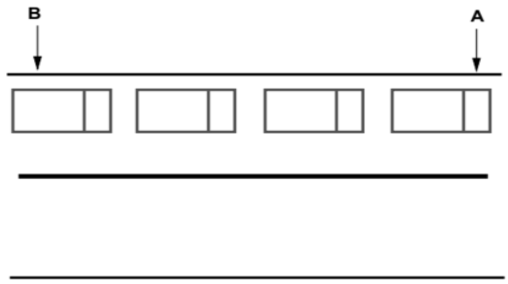

Fig. 5. Example of a road section with vehicles

Fig. 5. shows an example of a section of road, where points A and B correspond to the beginning and end of the monitored road section. The density of traffic on the road section is equal to the number of vehicles between points A and B, divided by the distance between A and B.

3) The volume of vehicles

The volume of vehicles is defined as the number of vehicles that pass a point on the highway or a certain lane for a certain period. Mathematically it is represented as the number of vehicles/hour:

$$q = \frac{n_t}{t}, \quad (4)$$

where *nt* is the number of vehicles crossing a point on the lane in a certain period of time *t*.

VI. THE MAIN TECHNOLOGIES USED TO BUILD ADAPTIVE CYBERPHYSICAL TRAFFIC CONTROL SYSTEMS

Transport detectors - allow to obtain data on the availability of transport on the road section, such transport parameters as speed and distance to the neighboring vehicle. Based on data from transport detectors, transport flow parameters are calculated [1].

Transport detectors for adaptive traffic control systems are divided into inductive detectors, video detectors, thermal imagers, and radars. The use of inductive detectors is based on the principle of electromagnetic induction. To install such detectors, we need to remove part of the pavement and install detectors. Inductive detectors often break down along with the pavement and also require regular maintenance. The problem with the use of inductive detectors is the inability to quickly eliminate the failure and the presence of erroneous readings. An example of an inductive detector is shown in Fig. 6. [18].

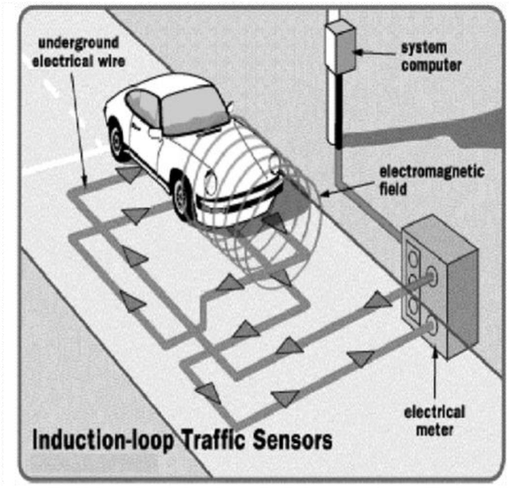

Fig. 6. Inductive detector

Detectors such as video detectors, thermal imagers, and radars do not require as much maintenance as inductive detectors. However, video detection relies on a lens that may not provide this information in the presence of interference, such as bad weather, low visibility of the car on the road, shadows, transient periods of daylight, glare in the sun, and headlights.

Other transport detectors include infrared and thermal vision devices. There are two types of infrared detectors - active and passive. Active infrared sensors work by transmitting energy from LEDs or laser diodes. In both types of detectors, the LED or laser diode illuminates the target, and the reflected energy is focused on a detector consisting of a pixel or an array of pixels. After that, the measured data is processed using various signal-processing algorithms to extract the desired information. Active infrared detectors provide data on the number, and speed of the car at night and day. The type of laser diode can also be used to classify cars, as it provides data on the shape of the car.

The passive infrared detector detects the energy emitted by objects in the field of view and can use signal-processing algorithms to extract the desired information. The advantages of infrared detectors are that they can work both day and night, and they can be installed both on the side and over the road. The disadvantage is that infrared sensors can be sensitive to adverse weather conditions. An example of a system using an infrared detector is shown in Fig. 7.

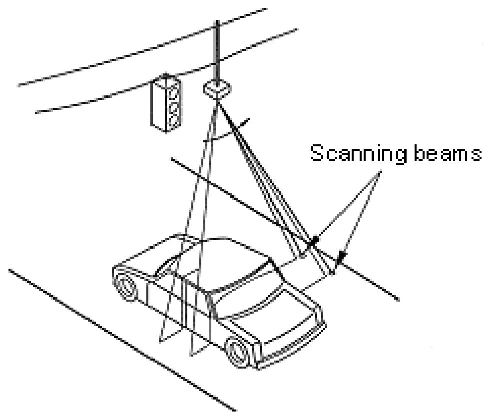

Fig. 7. System using infrared detector

Thermal vision devices cannot provide an accurate image in the event of extreme temperatures or interference, such as thermal shadows, and may erroneously account for vehicles with non-standard thermal signatures, such as electric vehicles.

Unlike video detectors or thermal imagers, radar detectors can provide higher signal accuracy even in low light, extreme heat, or adverse weather, regardless of the type of vehicle or the deterioration of the road surface.

Radar detectors use a continuous, frequency-modulated, or phase-modulated signal to determine the delay time of the feedback signal, thus calculating the distance to the detected vehicle.

Ethernet and GPRS (3G, 4G) technologies are used to connect detectors/controllers to the network.

Client-server architecture - allows division of the computing power between the nodes that monitor and nodes that are directly involved in calculating the parameters of traffic flows and make the decision to change the mode of operation of traffic lights directly.

VII. ANALYSIS OF EXISTING CYBER-PHYSICAL TRAFFIC CONTROL SYSTEMS

There are many examples of successful applications of cyber-physical traffic control systems in the world. Among them there are the following:

- The system of informing passengers, combined with the automated traffic control system (Helsinki, Finland), has reduced the total delay by 44 - 48%, the average travel time by 11%, and loss of time by 35,800-67500 man-hours per year.
- The creation of an adaptive traffic management system (Los Angeles, Auckland, USA) reduced the number of total traffic stops by 28 - 41%.
- Introduction of an adaptive traffic light management system with public transport priority (London, UK) reduced the average bus delay by 7-13%.
- Priority system for public transport (Southampton, UK) has reduced fuel consumption by buses by 13%, thereby reducing the overall level of emissions by 15%.
- The environmental effect occurs by reducing emissions of harmful substances (mainly into the atmosphere) and reducing noise levels in cities with a developed transport network.
- A public transport priority system implemented in Southampton, UK, has reduced bus fuel consumption by 13%, reducing overall emissions from 13% to 15%.

Examples of adaptive traffic control systems in Ukraine and around the world are the following:

1) SEA TCS – is a Ukrainian automated traffic control system developed by SEA company that allows to simultaneously regulate road traffic, monitor the performance of traffic lights, and control street lighting. Certified home traffic controllers (SEA RTC - Road Traffic Controller) are used to control traffic lights. These devices meet all the requirements of DSTU 4157: 2003 "Technical peripherals for automated traffic control systems". Performance of general system and server functions, data processing and exchange, functioning of software modules, WEB server, road controllers, and the system as a whole is supported by SEA TCS software, which includes built-in PC software, WEB interface, and database server.

2) InSync - is an adaptive traffic management system developed by Rhythm Engineering. The system uses modern sensor technology, image processing, and artificial intelligence. These elements are integrated into a system that automatically optimizes traffic light signals and coordinates traffic light signals along paved roads as needed in real-time. InSync uses a distributed network architecture that allows it to connect controllers to a large number of intersections.

Table 1

Comparison between adaptive traffic control systems

	SEA TCS	InSync	MASSTR
Goal	Minimize congestions and delays. Control street lightning.	Minimize congestions and detect traffic patterns.	Minimize congestions and fuel consumptions.
Architecture	Client-server & embedded	Client-server & embedded	Client-server & embedded
Detectors	Exhaust and inductive transport detectors	Radar transport detectors	Vehicle detection cameras
Green wave mode	Supported	Supported	Supported
Self-adaptation	Not supported	Supported	Not supported
Traffic flow parameters source	Intersection as standalone node	Intersection as standalone node	Intersection as standalone node

3) MASSTR - is an adaptive traffic management system commissioned by the Meadows Commission of New Jersey for the forty-square-mile area of the New Jersey Meadows area. Adaptive signal control technology adjusts the duration of traffic light cycles. This regional intelligent

transport system includes more than 128 traffic lights and serves more than 400,000 vehicles daily. MASSTR is one of several intelligent transportation systems projects deployed throughout New Jersey. MASSTR is the fourth largest deployment of SCATS (Sydney Coordinated Adaptive Traffic Adaptation System) in the United States.

All mentioned adaptive traffic control systems have both common and opposite features as well as strengths and weaknesses. The detailed comparison between the mentioned systems is shown in

Table *1*.

The mentioned systems share common goals and architectural approaches, use detectors for the calculation of traffic flow parameters, and support green wave mode. It is shown that the mentioned traffic control systems process traffic flow near a single intersection. One of the ways to enhance this approach is to use Ant colony optimization to have more evenly distributed traffic.

VIII. APPLICATION OF ANT COLONY OPTIMIZATION IN TRAFFIC CONTROL

The general approach is to represent the traffic network as a graph where intersections are nodes and roads are edges. Each edge has associated parameters such as distance, traffic flow, and delay. Ants in the Ant colony algorithm represent traffic agents. They move along the edges of the graph (roads) and deposit pheromone trails based on the quality of the route (e.g., low delay, fewer stops). Ants prefer to follow paths with higher pheromone concentrations. Initially, the pheromone levels on all edges are set to a small value. Ants are deployed from different intersections. Each ant selects a path probabilistically, biased by pheromone levels and heuristic information (e.g., distance). After an ant completes its journey, the amount of pheromone deposited on each edge is proportional to the quality of the path (e.g., inversely proportional to delay or stops).

The pheromone evaporates over time to prevent stagnation. Over several iterations, ants explore different paths, gradually converging towards more efficient routes.

As ants discover better paths with fewer stops, the pheromone concentrations on those paths increase, attracting more ants to explore them. The traffic signal timings are adjusted based on the accumulated pheromone levels.

Based on the traffic light controller classification scheme and chosen methods, an experimental system was developed. Unlike the common hierarchical structure of the automated traffic control systems, in the developed system the centralized approach using the city traffic control center is replaced by a decentralized approach using distributed decision-making nodes.

Experimental calculations with such configuration were made: count of intersection nodes 5, minimum green time 5s, maximum green time 30s, all red time 2s, minimum headway 2s, extension time 1s. To represent different possible scenarios when calculating traffic flow parameters for different values of speed, density, and number of vehicles (which corresponds to morning, noon, and evening road conditions) calculations with such configurations were made: simulation time 1h; speed 40 km/h, 20 km/h, 10km/h; number of vehicles to cross an intersection: 100, 200, 300.

A comparison of results between the developed decentralized experimental system and the centralized system is shown in Table 2:

Table 2

Comparison between centralized and decentralized traffic control systems

Approach	Vehicles speed	Vehicles count	Reduced stops	Reduced delay
Centralized	40 km/h	100	11.5%	15%
Centralized	20 km/h	200	16%	18%
Centralized	10 km/h	300	17.5%	21%
Decentralized with ACO	40 km/h	100	22%	28%
Decentralized with ACO	20 km/h	200	25%	35%
Decentralized with ACO	10 km/h	300	29%	39%

By analyzing experimental calculations it is discovered that decentralized adaptive traffic control systems that use Ant colony optimization distribute traffic more evenly and stops and delays are reduced by more than 10% comparing to other centralized traffic control systems.

By using the Ant colony algorithm in adaptive traffic control systems we can expect a reduction in the number of stops vehicles experience at intersections, leading to smoother traffic flow and decreased travel time. The extent of improvement would depend on various factors such as the complexity of the road network, dataset provided by traffic surveys, traffic patterns, and the efficiency of the ACO implementation.

IX. CONCLUSION

The article examined the causes and consequences of congestion, analyzed various tools and methods to solve the problem of congestion and delays. The traffic light of constant regulation was not perfect and had a number of shortcomings, including the accumulation of a large queue of cars in the event of a change in traffic intensity. This led to increased delays when crossing the intersection and, as a consequence, congestion. The adaptive traffic light changed the operating mode according to the current traffic situation.

Based on the analysis of methods used in related works, classification of traffic lights controllers was presented. Using presented classification of traffic lights controllers, optimal methods to address the problem of congestion and delays were chosen.

Based on chosen methods an experimental distributed traffic control system which implements Ant colony optimization algorithm was developed. In comparison with other centralized systems, the presented system showed 8-11% reduction in stops and 13-17% reduction in delays.

Future studies could also explore application of different variations of Ant colony optimization algorithm in the field of adaptive traffic control systems.

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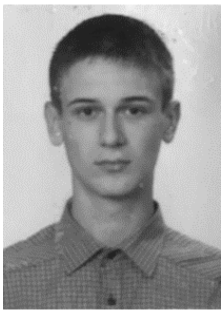

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