I. Khitrov. V. Nykonchuk, S. Pashkevych
National University of Water and Environmental Engineering, Rivne, Ukraine

OPTIMIZATION OF TRAFFIC SIGNAL CONTROL AT ROAD INTERSECTIONS

From a functional perspective, intersections are the most complex elements of road networks. This is where paths of traffic from different directions intersect, leading to various maneuvers. This underscores the importance of efficient traffic regulation, especially at intersections, in enhancing safety and improving efficiency. The article investigates the complex relationship between transportation infrastructure and the quality of public life, emphasizing the significance of effective traffic control, particularly at intersections, in enhancing safety and increasing efficiency. The research is aimed at optimizing traffic light management at congested four-way intersections in cities, with the goal of reducing congestion, increasing safety, and improving traffic flow. In most intersections with heavy traffic, traffic movement is regulated by traffic lights, and inefficient settings can lead to unjustified long waiting periods and increased overall traffic delays. For simulation modeling of traffic conditions at this intersection, PTV Vissim software was used. Observations of traffic flows, their distribution by direction, and parameters of traffic light regulation were used as input data for intersection modeling. The results of the modeling identified various approaches to optimizing traffic light management, including adjusting cycle times and considering passenger flows, with a particular emphasis on adaptive systems that respond to real-time traffic parameters. The study identifies challenges such as variable traffic flow and proposes solutions such as extending green phases and introducing pedestrian phases. It concludes by emphasizing the importance of collecting and interpreting dynamic traffic movement parameters for effective traffic light regulation, particularly in the implementation of automated traffic management systems.

Keywords: intersection, vehicle, traffic flow, traffic signal control, road conditions modeling.

INTRODUCTION

Transport and the quality of public life are inextricably related. This connection is greatly influenced by the role that highways, streets, and sidewalks play in our lives. Excellent transport connections are crucial for the development of the national economy.

From the functional point of view, the intersection is the most complex element of the road network. It is here that the traffic flows in different directions cross, and various maneuvers take place. This indicates that the intersection is a place with an increased concentration of conflict situations and an increased risk of traffic accidents.

At most of the high-flow intersections, traffic is controlled by traffic lights, and their inefficient operation can lead to unnecessarily long wait times and overall increase in traffic delays.

Therefore, it is extremely important to properly regulate road traffic in order to ensure the rational use of the intersection's potential, the increase in the throughput of all its elements, safety driving and efficiency [1, 2].

ANALYSIS OF LITERATURE DATA.

Traffic management in large cities is a complex and not always solved process, especially when it comes to managing intense traffic flows through regulated intersections. One of the primary tools for traffic management is traffic signalization, designed to organize the sequential movement of road users through intersections or specific street segments, as well as to mark hazardous zones on the road.

The optimization of traffic signal control regimes has attracted the attention of researchers in both domestic and foreign literature. Among them, studies by scholars such as V. P. Polishchuk, V. I. Eresov, M. P. Pechersky, Ye.Yu. Fornalchyk,, I. A. Mohyla, B. M. Chetverukhin, V. T. Kapitanov, Ye. O. Pidkhody, as proposed by [11-20], allow identifying the advantages of simulation modeling in the study of intersection functioning, applying various tools and mechanisms in adaptive control algorithms, and organizing traffic considering the needs of pedestrians and public transport. Scientific research by Reitzen, F. Webster, H. Inose, T. Hamada [22-25], and others.

Scientific works dedicated to various aspects of traffic management at regulated intersections in cities are studied by foreign scientists. Specifically, issues under investigation include analyzing the reliability of pedestrian crossings in urban conditions (Guo H.), determining current road and intersection capacities (Highway Capacity Manual), improving public transport priority systems at intersections (Kim W.), developing control algorithms based on fuzzy logic and simulation modeling (Kosonen I., Madhavan Nair B., Murat Y. Sazi), as well as optimizing response time to changes in traffic flow (Newell G., Noland R.).

Some studies explore the establishment and effectiveness of fixed and adaptive traffic signal control cycles (Miller A. J., Pappis C., Sosin J. A.) [11,13]. Possibilities of using basic knowledge for developing intersection control algorithms (Pranevicius H.) [17] and developing controllers based on fuzzy logic in the VISSIM environment are also investigated (Staniek M., Stotsko Z.) [12-14].

Thus, literary sources cover a wide range of problems related to traffic management at regulated intersections in cities, from pedestrian safety to the development of complex control algorithms.

Some aspects of traffic management at regulated intersections remain insufficiently researched or require further study. For example, integration with other transport systems, which could improve management efficiency and enhance safety, is often overlooked. Less attention is paid to environmental aspects and adaptive management, which could contribute to emissions reduction and energy consumption. Also important is considering the needs of pedestrians and cyclists, which significantly impacts safety and comfort in urban mobility.

FORMULATION OF THE PROBLEM.

The most significant issue at most existing traffic light installations is the constant increase in the number of vehicles, requiring continuous monitoring and timely response. The purpose of the research is to optimize traffic light control at a four-way intersection, adapting to road conditions, aimed at reducing congestion, improving safety and traffic flow, as well as enhancing the overall productivity of the transportation system.

The research analyzed a regulated intersection at the crossing of Stepana Bandery and Viacheslava Chornovola main streets in the city of Rivne. This intersection is characterized by constant significant traffic jams.

PURPOSE AND OBJECTIVES OF THE STUDY.

The main role of traffic lights, i.e. light signals for regulating traffic at intersections, is to separate (reduce) conflict situations between vehicles, pedestrians and other traffic participants at the intersections. Light signals regulate traffic flows in such a way as to allow vehicles from one flow group (non-conflicting or conflicting) to pass in a given time interval (phase), while vehicles from the other flow group are paused at the same time.

The regulation of vehicles is carried out based on a signal plan, which uniformly takes into account all flows grouped within phases. The main problem that needs to be solved when it comes to a signalized intersection is the calculation and optimization of the signal plan, which involves determining the length of the cycle, the number of phases, as well as the calculation of the distribution of green signal intervals for each phase (short cycles of 60-90 seconds are ideal for urban areas [3]). Traffic lights can operate in a fixed mode, when the signal plans are determined based on the pre-collected traffic data, and as adaptive systems, when the traffic lights operate depending on changes in traffic parameters, such as flow, speed, density and others.

Optimization of traffic light control at road intersections is a process aimed at improving the efficiency of the traffic light system to ensure the safety and smooth flow of vehicular traffic. This process may involve various aspects such as optimizing the timing of traffic light cycles, considering passenger flow, and installing sensors for automatic regulation (Figure. 1).

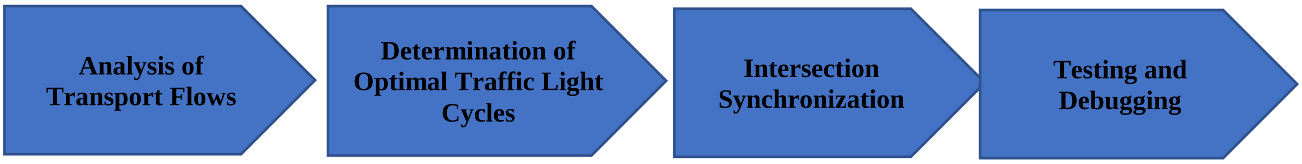


Figure. 1. Key Steps in Traffic Light Control Optimization

To model traffic conditions at the studied intersection with traffic light regulation, the research used PTV Vissim multimodal traffic simulation software [4].

RESEARCH RESULT.

An intersection, also known as a node, denotes the point where two or more road segments intersect, excluding access roads, and is delineated by the edges of the roads or, if absent, by the lateral boundary lines of the roadway.

Selecting the appropriate type of intersection for a given scenario can be a multifaceted and contentious decision. Regardless of the circumstances, the primary objective is to establish the safest feasible configuration of the intersection while ensuring an acceptable level of mobility, with the aim of optimizing traffic safety. The safety and requirements of all road users, including pedestrians and cyclists, especially those with disabilities or limited mobility, must be considered, as their needs can significantly influence decisions regarding traffic organization and management strategies.

Intersections are structured based on urban design principles, tailored to their specific location and the nature of present or anticipated regional development. This process considers the potential necessity for revised traffic organization, implementation of traffic light controls, projected traffic volume, and vehicle size considerations.The constructive elements of the studied intersection are shown in Figure. 2.

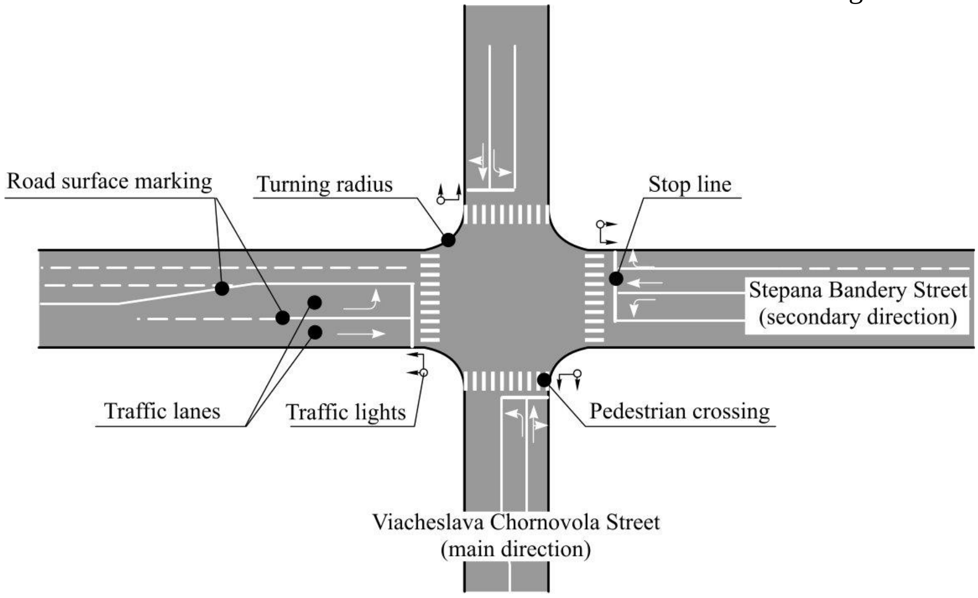


Figure. 2. Basic elements of the studied four-way intersection in the city of Rivne

The organization of the traffic at the intersection is mainly determined by the intensity of the traffic flow. At a low traffic intensity, the intersection can function as an unregulated one, and as the flow increases, the organization of traffic at the intersection becomes possible only with the use of traffic signals (Figure. 3).

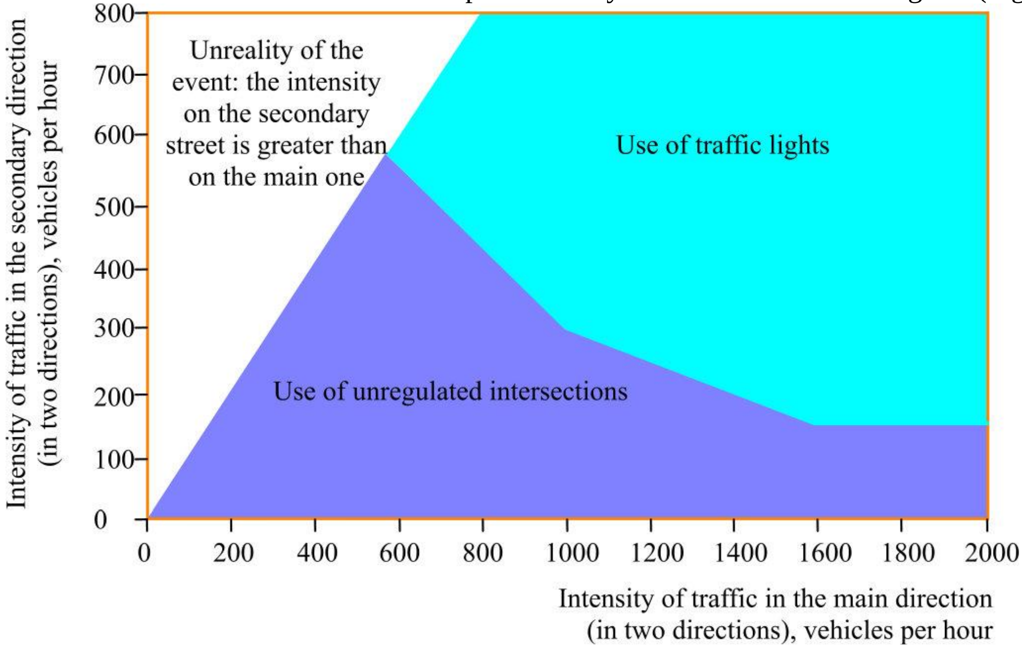


Figure. 3. Conditions for the use of various types of traffic management at intersections [5]

Traffic light regulation is one of the measures commonly used at intersections to minimize travel time and delays for vehicles and/or pedestrians. Traffic light regulation at intersections allows traffic control by allocating time slots during which separate traffic flows at each approach to the intersection can use the available road space [6].

DISCUSSION OF THE RESULTS OF THE STUDY.

Regulated with traffic lights intersections in the city of Rivne are controlled using a fixed time (all signal parameters are calculated in advance and kept constant based on the traffic data). This method usually shows good results under normal traffic conditions, but it sometimes fails to cope with complex time-varying traffic conditions.

From the point of view of planning, systems with a fixed mode are most often implemented as static, with a constant cycle length during the day, and dynamic, which take into account the non-stationarity of the traffic flow during the day. In dynamic systems, the day is divided into a number of time intervals, assuming that for each separate time interval, traffic flows are constant [7].

There are three main concepts that describe the sequence of traffic signals – cycle, phase and duration: cycle (the total time required to complete one sequence of signals for all movements at the intersection), phase (unit of controller time associated with one or more movements) and duration (the amount of time the signal is displayed in each phase) [8]. Furthermore, a traffic flow group is defined as one or more compatible movements of road users, and each phase has a set of time slots for each traffic flow group.

The main problem that must be solved when considering isolated traffic light intersections is the calculation and optimization of the signal plan, which involves: determining the number of phases; determining cycle duration; distribution, i.e. determining parts of available green time for each phase; modeling of traffic situations that may arise due to the passage of priority vehicles, congestion of vehicles in intersection areas during peak periods or other situations. At the same time, it is necessary to achieve the best possible characteristics of the intersection functioning.

At the studied intersection, two-phase traffic light regulation with fixed cycles for the main direction (Viacheslava Chornovola Street, 30 seconds) and the secondary direction (Stepana Bandery Street, 30 seconds) is used (Figure. 4).

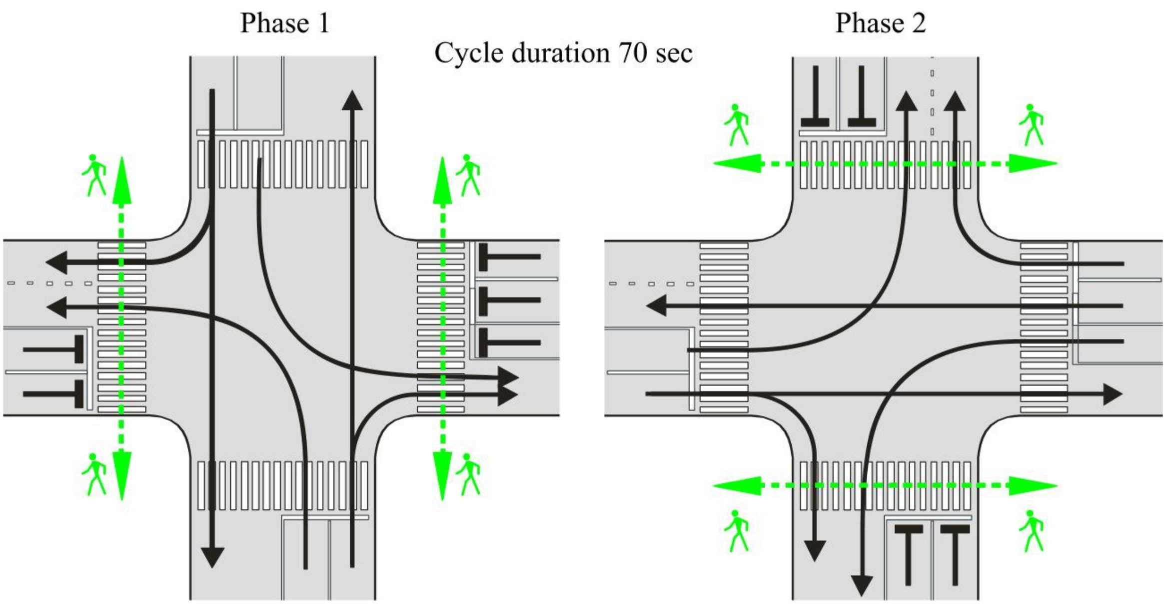
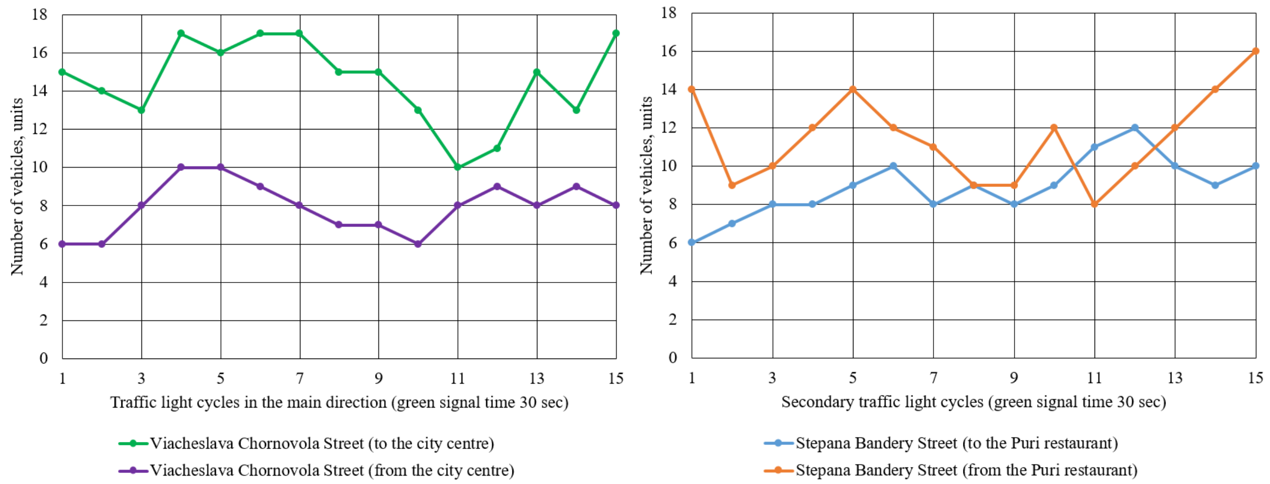


Figure. 4. Traffic light regulation at the Viacheslava Chornovola and Stepana Bandery streets intersection, city of Rivne

The flow of vehicles that pass through the intersection during one cycle of the traffic light signal is uneven, ranging from 17 to 6 vehicles and depends on the time period. The traffic flow reaches its peak during the commuting time (Figure. 5).



а) *б)*

Figure. 5. Number of vehicles that pass through the intersection during one cycle of the traffic light signal for the main (a) and secondary (b) direction

An increase in the number of trucks and buses in the traffic flow is accompanied by a decrease in the number of vehicles that pass the intersection, which is explained by their lower speed, more time spent on the start of movement and other factors (Figure. 6).

The maximum throughput of the intersection is determined by the theoretical possibility of the traffic flow to pass the selected node at the most probable speed within one hour.

The saturation flow is the flow of vehicles from the queue in front of the stop line, which move according to the permissive signal of the traffic light [8]. In its essence, it is a traffic flow that exists when the roadway (traffic lane) is operating at throughput capacity.

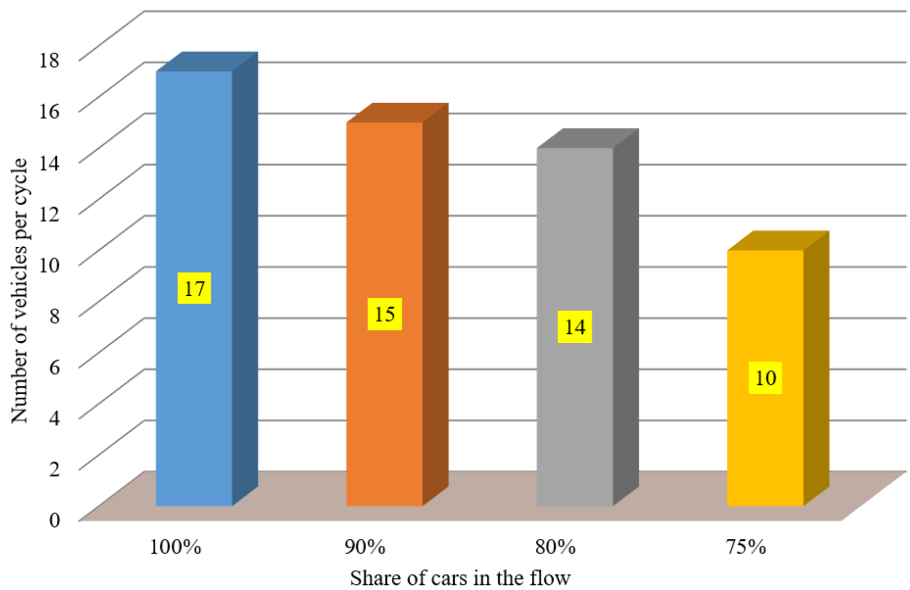


Figure. 6. Throughput capacity of the intersection for one cycle of traffic light regulation depending on the composition of the traffic flow

An important assessment indicator, which characterizes the functioning of the intersection and depends primarily on its geometric parameters, is the degree of saturation of traffic directions, that is, the maximum intensity of vehicles per hour through the intersection. The average value is 724 cars, which indicates overloading of the studied intersection and requires its redesigning by changing the duration of traffic light regulation (Figure. 7).

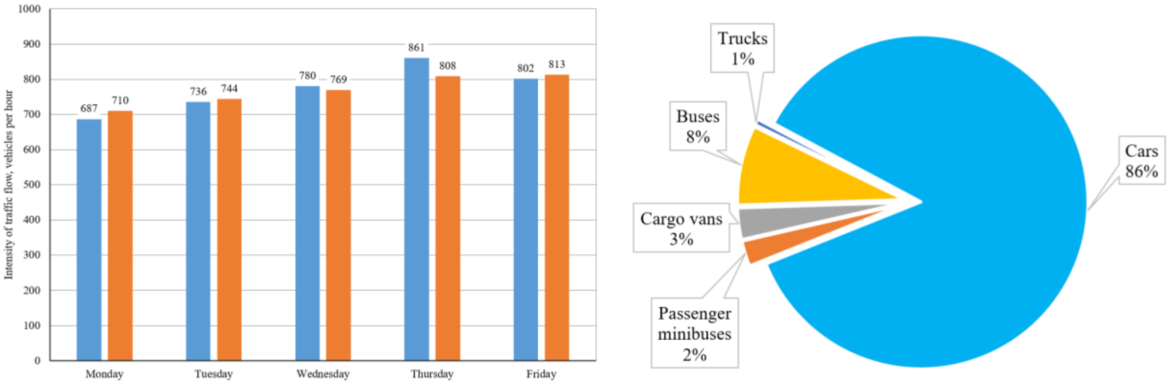


Figure. 7. Structure of the traffic flow in the main direction – Viacheslava Chornovola street (8:00-9:00 a.m.)

The studied intersection uses to 60-70% of its throughput capacity according to the selected cycles of the traffic light regulation and needs their optimization or significant changes in the organization of the traffic flow (Figure. 8).

The number of vehicles in the queue affects the throughput capacity of the intersection and the speed of the flow. In particular, when the queue of vehicles increases to 20 units, the throughput capacity of the lane decreases by 1.5-2 times.

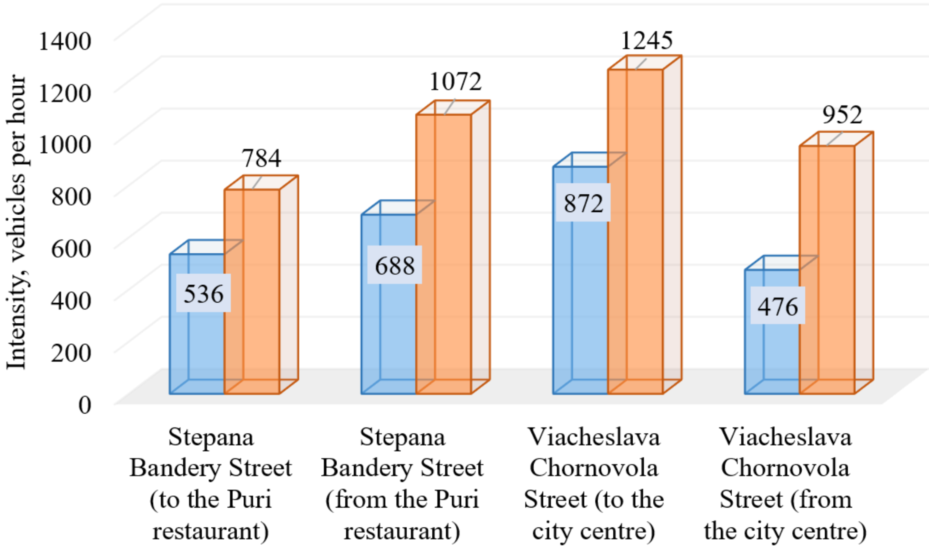


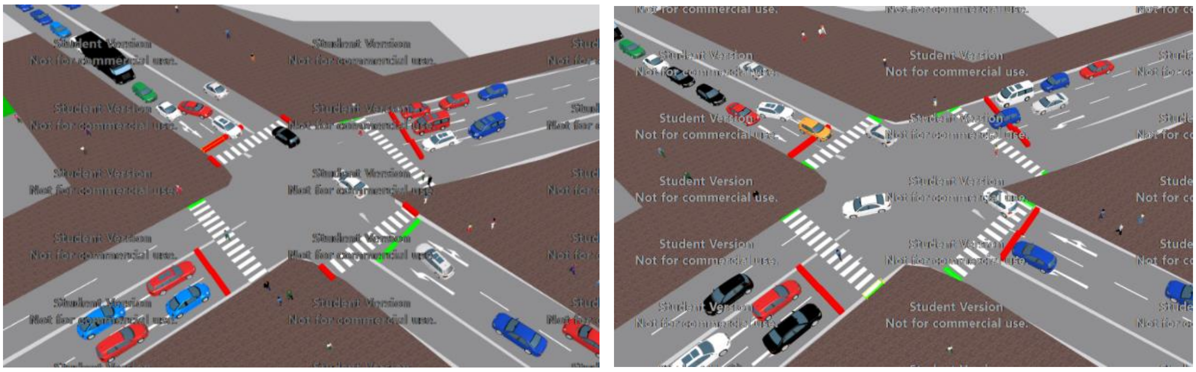
Figure. 8. Actual and estimated indicators of the traffic flow by direction (averaged values)

According to the research results, the road conditions were modeled and the signal plan was optimized with the use of PTV Vissim software. Simulation modeling of the intersection included drawing a road network, installing traffic lights (signal controllers) with a description of their work (choosing the type of light signaling devices, creating signal groups and traffic light signals, parameters for coordinating signals), forming pedestrian zones and a node, performing calculations with subsequent analysis of the received data.

In order to improve the efficiency of the intersection, two options for the operation of the traffic light controllers are offered (Figure. 9):

1. Lengthening of the “green” phase, for the convenience of turning to the left (by reducing the phase of oncoming traffic in one direction by 5 seconds). The total duration of the cycle of 70 seconds will not change;

2. Implementation of the third phase – fully pedestrian in all directions, lasting 20 seconds. The total duration of the cycle will increase to 90 seconds.



а) *б)*

Figure. 9. Options for modeling traffic light regulation modes by extending the “green” phase (a) and implementing the third pedestrian phase (b)

Such changes are needed because it is quite difficult to make a left turn at the intersection. Although the studied intersection has two (in one direction – three) traffic lanes, the extreme one of which is intended for making a left turn, the number of vehicles that can perform such a maneuver at the permissive traffic light signal remains low and, in the best case, makes 3-4 vehicles.

In addition, the close location of another regulated intersection 500 m away for both the main and secondary directions, from which the queue of vehicles quite often reaches the studied intersection, reduces the capacity of the studied intersection with the frequent formation of traffic jams (Figure. 10). Therefore, the disruption of the traffic flow in all directions at the same time will be an effective measure, which can be implemented during peak periods of traffic accumulation.

Figure. 10. Formation of a traffic jam at the intersection due to a significant accumulation of vehicles at the exit

A more progressive measure can be the introduction of adaptive systems, which are based on new traffic monitoring technologies and allow obtaining accurate data on traffic flows in real time and performing adaptive control of traffic lights, that is, adapting the signal plan in real time to changes in traffic flows (Figure. 11). The solution based on the proposed algorithm simplifies the use of the system, and also requires significantly lower costs for its implementation and maintenance [9,10].

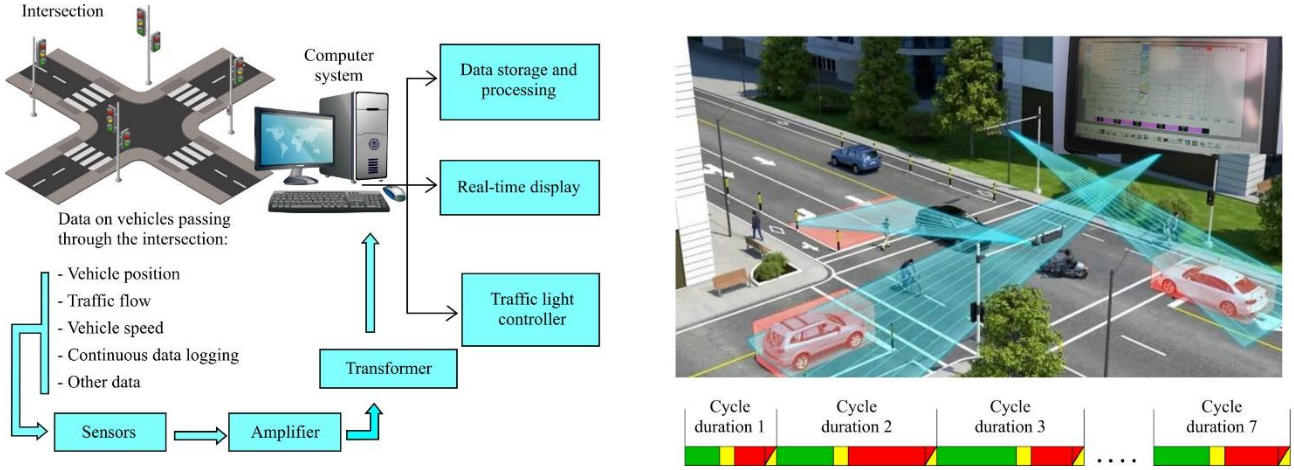


Figure. 11. Adaptive traffic light control system

One of the main requirements for the successful deployment of an effective, city-wide, automated traffic control system is an accurate estimation of the number of vehicles on the roads (this can be achieved in various ways, such as the use of inductive loops, magnetic sensors, magnetometers or even cameras).

SUMMARY

Thus, a successful solution to the effective operation of the traffic light regulation of the intersection requires the collection and interpretation of dynamic parameters of traffic flows; elimination or minimization of the possibility of traffic jams by changing the duration of both a separate phase and the entire traffic light cycle; determining the relationship between the parameters of the queue of outgoing vehicles and the throughput capacity of the intersection.

In the case of using an automatic system when receiving dynamic data about the traffic flow, the obtained data can serve as a basis for developing an algorithm for controlled regulation of the duration of the permissive traffic interval for the formation of a queue of vehicles entering the intersection.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data will be made available on request.

REFERENCES

1. Radivojević, M., Tanasković, M. & Stević Z. (2021). The adaptive algorithm of a four-way intersection regulated by traffic lights with four phases within a cycle. *Expert Systems with Applications*, Vol. 166, 114073.

2. Khitrov, I. (2023). Modelling of the safe traffic conditions of the inter-section with nearby railway tracks. *Avtoshliakhovyk Ukrayiny*, Issue 1, 30-34. DOI: 10.33868/0365-8392-2022-1-273-30-34 [in Ukrainian].

3. Signal Cycle Lengths. *National Association of City Transportation Officials* : website. URL: https://nacto.org/publication/urban-street-design-guide/intersection-design-elements/traffic-signals/signal-cycle-lengths/.

4. *PTV Vissim* (2021). Germany. PTV Planning Transport. Verkehr AG.

5. Dziubynska, O. V., Smal, M. V. (2015). Orhanizatsiia ta bezpeka dorozhnoho rukhu [Traffic organization and safety]. Lutsk: RVV Lutskoho NTU [in Ukrainian].

6. Lee, J., Park, B. Development and evaluation of a cooperative vehicle intersection control algorithm under the connected vehicles environment. *IEEE Transactions on Intelligent Transportation*

Systems, 2012. 13(1), pp. 81–90.

7. Zijun Liang, Xuejuan Zhan, Wei Kong & Yun Xiao. (2023). Space-Time Resource Integrated Optimization Method for Time-of-Day Division at Intersection Based on Multidimensional Traffic Flows. *Journal of Advanced Transportation*, 1-18.

8. Fornalchyk, Ye. Yu., Mohyla, I. A., Trushevskyi V. E. & Hilevych V. V. (2018). Upravlinnia dorozhnim rukhom na rehulovanykh perekhrestiakh u mistakh [Traffic management at regulated intersections in cities]. Lviv : Vydavnytstvo Lvivskoi politekhniky [in Ukrainian].

9. S. Pashkevych, V. Nykonchuk, M. Krystopchuk (2023) Assessment of the capacity of the city road network taking into account the parking offer. *Advance in mechanical engineering and transport /* Issue 2, 21. DOI: https://doi.org/10.36910/automash.v2i21.1221

10.Han Zhang, Henry X. Liu, Peng Chen, Guizhen Yu &Yunpeng Wang. (2020). Cycle-Based End of Queue Estimation at Signalized Intersections Using Low-Penetration-Rate Vehicle Trajectories. *IEEE Transactions on Intelligent Transportation Systems*, Vol.21 (8), 3257-3272.

11.Miller, A. J. (1963). Setting for Fixed-cycle Traffic Signals. *Operational Research Quarterly*, 4, 373–386.

12.Staniek, M. (2011). The crossroads lights fuzzy controller development principles in VISSIM environment. *Zeszyty Naukowe Politechniki Slaskiej. seria Transport*, 73(1861), 87–95.

13.Sosin, J. A. (1980). Delays at Intersections Controlled by Fixed-Cycle Traffic Signals. *Traffic Engineering and Control*, 21(8), 407–413.

14.Sysyuk, H. Y., Motolyha, O. M., & Skryl, I. K. (2009). Simulation Model of Traffic Flow at Intersections. Bulletin of Kremenchuk State Polytechnic University named after Mykhailo Ostrohradskyi, 1(59), 28–32.

15.Polishchuk, V. P., & Dziuba, O. P. (2008). Traffic Flow Theory: Methods and Models of Traffic Organization (Educational manual). Kyiv: Znannia Ukrainy.

16.Yeresov, V. I., & Khristenko, O. V. (2009). Comprehensive Assessment of the Efficiency of Traffic Light Control at Intersections. Bulletin of the National Technical University of Ukraine, 19(2), 72-77.

17.Pranevicius, H., & Kraujalis, T. (2012). Knowledge based traffic signal control model for signalized intersection. *Transport*, 27(3), 263–267.

18.Stotsko, Z., Fornalchyk, Ye., & Mohyla, I. (2013). Simulation of signalized intersection functioning with fuzzy control algorithm. *Transport Problems*, 8(1), 5–16.

19.Madhavan Nair, B., & Cai, J. (2007). A fuzzy logic controller for isolated signalized intersection with traffic abnormality considered. In *Proceedings of 2007 IEEE Intelligent Vehicles Symposium* (pp. 1229–1233).

20.Fornalchyk, Ye., Mohyla, I., & Hilevych, V. (2013). The saturation flow volume as a function of the intersection passing speed. *International Scientific Journal "Transport Problems"*, 8(3), 43–51.

21.Fornalchyk, Y. Y., Mohyla, I. A., Trushevskyi, V. E., & Hilevych, V. V. (2018). Traffic Management at Regulated Intersections in Cities. Lviv: Lviv Polytechnic University Press.

22.Inose H. Road traffic control / H. Inose, T. Hamada, E. Posner. – 1975. – 320 p. 181. Kim W. Improved transit signal priority system for networks with nearside bus stops / W. Kim, L. Rilett //Transportation Research Record: Journal of the Transportation Research Board. – 2005. – T. 1925. – No. 1. – pp. 205–214.

23. Guo, H. (2012). Reliability analysis of pedestrian safety crossing in urban traffic environment. *Safety Science*, 50(4), 968–973.

24.Chow, A. H. F. (2015). Optimization of dynamic motorway traffic via a parsimonious and decentralized approach. *Transportation Research Part C*, 55, 69–84.

25.Kim, W., & Rilett, L. (2005). Improved transit signal priority system for networks with nearside bus stops. *Transportation Research Record: Journal of the Transportation Research Board*, 1925(1), 205–214.

*Viktoriia NYKONCHUK**. Sc (Economics), Professor, Hard of the Transport Technologies and Technical Service Department, National University of Water and Environmental Engineering https://orcid.org/0000-0001-7515-6016

Ihor KHITROV, Ph.D, Associate Professor, Associate Professor of the Transport Technology and Technical Service Department, National University of Water and Environmental Engineering://https:// https://orcid.org/0000-0003-2310-1472

Svetlana PASHKEVYCH Senior Lecturer of the Transport Technology and Technical Service Department, National University of Water and Environmental Engineering https://orcid.org/0000-0001-7667-8932

* Corresponding author.

Received 20 February 2024;
Accepted 30 April 2024
Available online 28 May 2024

DOI: 10.36910/conf_avto.v1i1.1388