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MULTI-AGENT MODELING OF TRAFFIC ORGANIZATION IN URBAN AGGLOMERATIONS

Summary. *The authors consider the features of multi-agent modeling for traffic optimization in the central areas of cities. While evaluating the unique challenges associated with the high concentration of vehicles, pedestrians and historical buildings, the potential of multi-agent systems to effectively solve the problem of congestion, safety and quality of life in urban areas is investigated. The potential of multi-agent modeling in the context of traffic management in the central areas of the city allows us to identify the key challenges and opportunities. Many scientists address the main aspects of such modeling and use them in the transport and road sectors. A review of current research and development has shown that multi-agent models aim to simulate and optimize the supervision and control of transportation in various traffic scenarios. Modeling traffic organization in the central areas of cities is one of the main elements of urban development planning and management. Due to the growing population of cities and the increasing number of vehicles, the problems of congestion, air pollution, and inefficient use of infrastructure are becoming increasingly relevant. Therefore, it can be noted that multi-agent traffic modeling opens up new prospects for developing effective traffic management strategies, providing a flexible and adaptive solution to these problems. The research analyzes the existing approaches, identifies the system`s key components, and develops a model that demonstrates the interaction between agents and the environment based on a mathematical description. A practical simulation of the model, carried out using the AnyLogic software on the example of Lesia Ukrainka Boulevard in Kyiv, confirms the effectiveness of the multi-agent approach. The results of the study indicate the possibility of applying the developed model to improve intelligent information systems for traffic flow management, which opens up new prospects for improving traffic in the central areas of cities.*

Keywords: *multi-agent modeling, traffic, information systems, optimization, traffic flow, AnyLogic, agent, mathematical model, intelligent systems.*

1. INTRODUCTION

In recent decades, multi-agent modeling has been actively developing as one of the most promising approaches in studying complex systems involving the interaction of multiple autonomous agents, each with its own goals and ability to act independently. In the case of traffic management and organization, multi-agent modeling opens up new horizons for traffic analysis, planning, and optimization, particularly in central areas of the city where traffic density and intensity of road infrastructure use are the highest.

City centers often face unique and complex challenges in traffic management due to the high concentration of public transport, private cars, pedestrians, and cyclists. In addition, historical buildings, limited spatial planning, and high requirements for preserving historical heritage impose additional restrictions on the possibilities of reorganizing road infrastructure. In such conditions, multi-agent

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modeling becomes not just a relevant tool, but often the only possible way to effectively solve the problem with traffic optimization, ensure road safety, and improve the overall quality of life of the urban population.

2. RESEARCH STATEMENT

The problem of multi-agent modeling of traffic organization in the central areas of the city is not only to solve logistical problems but also to ensure a high level of safety, reduce environmental pollution, and create comfortable living conditions for residents. These aspects are especially important in the context of preserving the historical appearance of central areas and the need to adapt the existing infrastructure to modern mobility requirements.

The aim of the article is to study the potential of multi-agent modeling and to build a simulation model based on it to optimize traffic organization in the central areas of the city using information systems and technologies. The article seeks to identify the possibilities of a multi-agent approach to improve the efficiency, safety, and sustainability of urban transportation systems.

The following tasks need to be solved to achieve this goal:

- analysis of existing approaches to multi-agent modeling in the context of traffic management
- forming the structure of multi-agent models of traffic organization and traffic flows;
- identification of the main components of the system, in particular agents and their properties, states, and actions, as well as a description of the environment in which their interaction takes place;
- conducting a practical simulation of the model using software to demonstrate its effectiveness and analyze the results.

3. LITERATURE REVIEW

Multi-agent systems (MAS) are used to model complex systems where each agent represents a separate entity with its goals and interaction capabilities. In traffic management, agents can be cars, traffic lights, road sensors, et cetera. Modern MAS can analyze a large amount of data in real-time and adapt traffic management to minimize congestion and increase the overall capacity of the road network.

One approach to mathematically describe traffic dynamics is to use the Nagel-Schreckenberg model [1] to simulate traffic on a single lane. It represents cars as agents moving on a grid with fixed rules. However, for a multi-agent system with different road users and complex infrastructure, a more comprehensive approach is required.

The concept of multi-agent modeling in the context of traffic management in city centers allows us to identify the main challenges and opportunities. Many scientists address the main aspects of such modeling and use them in the transport and road sectors. A review of current research and development has shown that multi-agent models aim to simulate and optimize traffic supervision and control in various traffic scenarios. One of the approaches is to use a network communication model in automobile and urban traffic [2, 3]. Aleksandar, Dukić et al. note that such a model consists of intelligent interactive teams of human, software, and cyber-physical agents. Another approach proposed by Jinghui Wang is to apply multi-agent theory to model complex elements in traffic using cellular automata, which can effectively simulate complex traffic scenes [4].

An analysis of different approaches and solutions proposed by scientists and engineers from many countries shows that their attention is drawn to managing traffic lights and traffic signal objects. In his study, Wang Shangbo proposes a Friend-Deep Q-network (Friend-DQN) approach for controlling multiple traffic lights in urban networks, which uses agent cooperation to reduce the state space and improve convergence [5].

Dongjiang Liu and Leixiao Li focus on improving communication efficiency and strengthening learning algorithms for traffic signal synchronization in decentralized multi-agent traffic signal control algorithms [6]. Robert E. Mace, in his paper, proposed a new algorithm called CoevoMARL for controlling traffic signals at multiple intersections using multi-agent reinforcement learning. The author focused on capturing the spatial relationship between traffic signals and included a temporally stable traffic pattern [7].

Multi-agent models are also being considered as a traffic management and decision-making tool. The intensive development of innovative technologies has made it possible to consider methods such as reinforcement learning and graphical neural networks to improve the efficiency and safety of autonomous vehicles on the road. For example, Huanbiao et al. developed a decentralized multi-agent proximal policy optimization (MAPPO) system that uses attention representations to make joint decisions at intersections [8]. Anum Mushtaq et al. proposed a multi-agent reinforcement learning approach with Smart routing to optimize traffic light control and improve the flow of autonomous vehicles [9]. Nguyen-Tuan-Thanh Le investigated using multi-agent reinforcement learning to study congestion on one-way multilane highways [10]. Qi Liu et al. presented an integrated framework using graph reinforcement learning techniques to model vehicle interactions and improve multi-agent decision-making in intelligent transportation scenarios [11].

Mariam Zouari proposed a cooperative multi-agent system (MAS) for making traffic decisions in a vehicular ad-hoc network (VANET) based on a hierarchical fuzzy knowledge representation system used to guide the travel route [12].

Faza Fawzan Bastarianto discusses agent-based models for transportation simulation and analysis, pointing out the complexity, adaptability, and heterogeneity of transportation systems that can be effectively simulated using agent-based modeling [13].

These researches reveal the potential of multi-agent models in improving the processes of traffic organization and management. Therefore, there is a need for further research and development of multi-agent models that will help transform the central areas of cities into more comfortable and safe spaces for all road users.

4. MAIN PART

Traffic modeling in city centers is one of the main elements in urban development planning and management. Due to the growing population of cities and the increasing number of vehicles, the problems of congestion, air pollution, and inefficient use of infrastructure are becoming increasingly relevant. Therefore, it can be noted that multi-agent traffic modeling opens up new prospects for developing effective traffic management strategies, providing a flexible and adaptive solution to these problems.

The complexity and dynamism of urban transportation systems cause the necessity for a multi-agent approach to traffic modeling. Traditional methods are often unable to adequately reflect the interaction between different road users, real-time changes in traffic conditions, and adapt to the ever-changing needs of the city. Multi-agent modeling, on the contrary, allows reproducing in detail the behavior of individual agents (cars, traffic lights, pedestrians) and their interaction in a complex system, which leads to high realism and accuracy of the model.

The basics of multi-agent modeling are considered by many researchers who determine the importance of applying mathematical methods to optimize the functioning and coordination of several agents in a particular system [13, 14]. The advantages of multi-agent modeling include the following:

- ability to scale and modify;
- easy adaptability to the specific needs of a city or district, which allows for changes in agent behavior, road infrastructure, traffic rules, et cetera;
- high flexibility in predicting the consequences of various traffic management strategies, which contributes to solving complex optimization and planning problems.

To implement multi-agent modeling, it is necessary to define the main components of the system, including agents, their states and actions, as well as describe the environment in which the interaction takes place. An important aspect is the development of rules of interaction between agents and algorithms for their behavior, which will allow the reproduction of realistic traffic dynamics. In addition, it is necessary to consider the variability of transport needs during the day and the impact of various factors (weather conditions, road works, accidents) on traffic organization.

The first stage of building a model is to identify the main blocks that form the basis for further actions. Thus, we can identify the main triad (agents, environment, interaction), which is detailed and broken down at the micro level (Fig. 1).

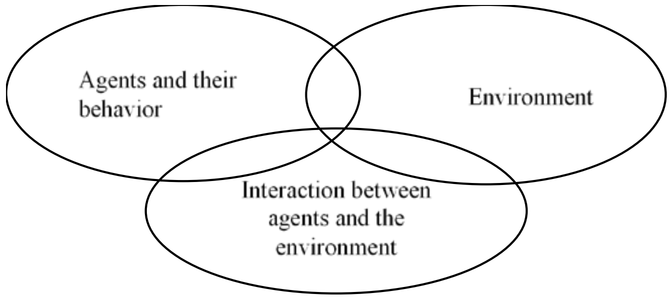

Fig. 1. Structural triad of the model

As the traffic flow consists of a variety of road users, the model should include different types of agents (cars, public transport, pedestrians, et cetera) with their own characteristics and behavioral algorithms. It allows the simulation of realistic scenarios of interaction and conflicts on the road, as well as the development of strategies to resolve them.

The model environment includes the city road network with all its characteristics (road signs, traffic lights, intersections, et cetera). It allows taking into account physical constraints and regulatory requirements when planning routes and managing traffic flows.

Ensuring dynamic interaction between agents and the environment is a key aspect of the model. It includes not only the interaction of agents with each other but also their interaction with the road infrastructure, which may change over time (e.g., changes in traffic signals).

Identification of the main components of a mathematical multi-agent model and the development of a mathematical description of interaction on their basis is a fundamental stage in creating an information system for traffic flow management and monitoring. Table 1 shows a description of the model components.

Table 1

Main components of the model

No.	Model component	Description of the component
1	Agents ***(A)***	Each $\boldsymbol{a_i}$ agent represents a vehicle: $\boldsymbol{A=\{a_1,a_2,...,a_N\}}$. Agents have their own set of characteristics and behavioral rules that allow them to respond to changes in the traffic environment. Agents can interact with each other and the city's infrastructure to move efficiently and prevent traffic congestion.
2	State of the agent $\boldsymbol{S(a_i,t)}$	The state of the agent is determined in a certain moment in time, as $\boldsymbol{S(a_i,t) = (x_i(t), y_i(t), v_i(t), d_i(t))}$, where $\boldsymbol{(x_i(t), y_i(t))}$ – agent coordinates on the map, $\boldsymbol{v_i(t)}$ – speed, $\boldsymbol{d_i(t)}$ – direction of movement
3	Actions of the agent $\boldsymbol{A(a_i)}$	Actions that the agent can perform include changing the speed $\boldsymbol{\Delta v_i}$, change of direction $\boldsymbol{\Delta d_i}$, and possibly stopping
4	Environment ***(E)***	The environment includes the city's road network with its parameters, such as speed limits, traffic lights, and other infrastructure
5	Environment condition $\boldsymbol{S_E}$	The environment condition can be represented by a matrix ***M***, where each element of the matrix contains information about the road section (e.g., free or busy, presence of obstacles)

Considering the characteristics of the components of the triad, it can be noted that the model must be flexible to adapt to changing traffic conditions and the needs of the city. Scalability will allow considering the expansion or modification of the road network, as well as changes in the number of traffic flows. This approach provides the ability to implement innovative solutions and adapt the system to future challenges.

Here is a detailed diagram based on the description of the main components of the multi-agent model of traffic management in the central areas of cities. This visualization represents the interaction between agents, their states and actions, as well as the environment and its characteristics (Fig. 2).

Creating a mathematical multi-agent model of traffic organization and traffic flow management in central districts of the city requires a clear understanding of the interaction between agents (vehicles) and the environment (road infrastructure). The mathematical description of this interaction requires the definition of basic functions and formulas that will allow the modeling of the system`s behavior in real-time conditions. A conceptual scheme of the multi-agent model was developed based on the above aspects, which is shown in Fig. 3.

Fig. 2. Schematic description of the main components of the model

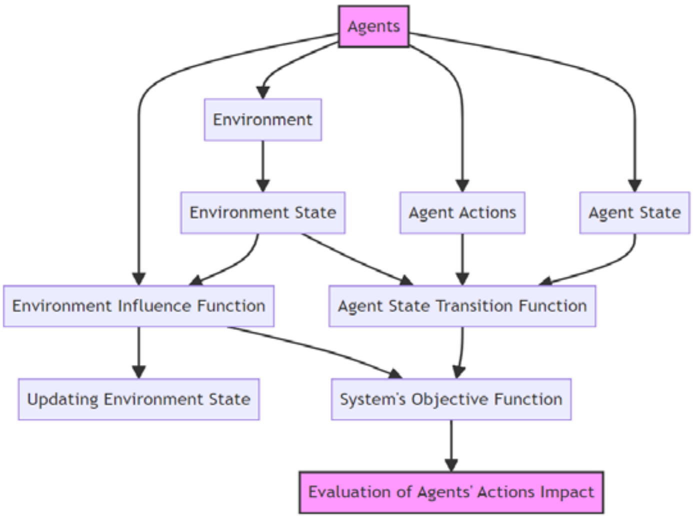

Fig. 3. Conceptual diagram of a multi-agent model of traffic organization and traffic flows

The research of the main characteristics of the object of study allowed us to form a mathematical description of the interaction, which is carried out through the functions of transition of states of agents and the environment and is presented in Table 2.

Table 2

Mathematical formulation of the interaction

	Agent state transition function	Function of influence on the environment	Target function of the system
Formula.	$\boldsymbol{S'_{a_i}} = \boldsymbol{f(S(a_i,t), A(a_i), S_E)}$, where $\boldsymbol{S'_{a_i}}$ – new state of the agent after the action $\boldsymbol{A(a_i)}$ is performed in the environment $\boldsymbol{S_E}$.	$\boldsymbol{S_E{'}=g(S_E,A)}$, where $\boldsymbol{S_E{'}}$ – the new state of the environment after all agents $\boldsymbol{A}$ have completed their actions.	$\boldsymbol{F(S_E,A)=\!\longrightarrow min\ max}$, where $\boldsymbol{F}$ – is a function that minimizes congestion and maximizes the capacity of the transport network**.**
Description	reflects how the state of each agent changes as a result of its actions and the influence of the environment	provides modeling of changes in the environment that occur as a result of the actions of agents	is the basis for optimizing traffic flow management, as it defines the overall goal of the system, such as minimizing congestion or maximizing capacity

The agent state transition function is based on dynamic modeling, where the agent state is updated according to its current state, selected actions, and the state of the road environment. The mathematical representation allows you to precisely determine how the agent's speed, direction of movement, and coordinates change over time:

$$\begin{cases} x_i' = x_i + v_i \cos(d_i)\Delta t, \\ y_i' = y_i + v_i \sin(d_i)\Delta t, \\ v_i' = v_i + \Delta v_i, \\ d_i' = d_i + \Delta d_i. \end{cases} \qquad (1)$$

The environmental impact function considers how the collective actions of all agents affect the road network, for example, changes in the occupancy of road sections. It includes analyzing traffic distribution and identifying potential congestion. The environment is updated based on the actions of the agents and the changes that occur as a result of these actions, such as changes in the occupancy of road sections:

$$M' = h(M, \{S_{a1}', S_{a2}', ... S_{an}'\}), \qquad (2)$$

where M' – updated road network status matrix, which reflects the occupancy of sections after agents move.

The system`s objective function summarizes the impact of individual agents and environmental conditions on the overall performance of the traffic system. take into account various aspects, such as total travel time or total delays, and be defined as:

$$F(S_E, A) = \sum_{i=1}^{n} w_i C_i (S_E, A), \qquad (3)$$

where C_i – specific criteria (e.g., travel time for an agent a_i); w_i – weighting coefficients to balance different aspects in the goal function.

These functions provide the basis for dynamic interaction between agents and the environment, allowing the system to effectively adapt to constantly changing traffic conditions.

The mathematical formulas for changing the agent's state and updating the environment were developed based on dynamic modeling and system theory. Using equations of motion allows for considering physical constraints and rules of agent behavior. These formulas integrate parameters such as the speed and direction of movement of agents, as well as external conditions such as the state of the road network. They allow you to predict the development of the situation on the roads, adapt traffic management strategies to changing conditions, and ensure effective interaction between road users.

Analyzing agents' behavior requires a deep understanding and analysis of their dynamic relationships. The most important aspects of such relationships are cooperation and conflict of interest between agents.

Cooperation between agents is a key element for ensuring efficient and safe traffic in cities and can be represented through the interaction of their actions:

$$A_{coop} = \bigcap_{i=1}^{n} A(a_i), \qquad (4)$$

where A_{coop} – a set of actions leading to the achievement of a common goal.

Traffic coherence is created through the interaction of agents' actions, which reduces the likelihood of congestion and increases the overall capacity of the road network. For example, agents (cars) can share information about road conditions or their routes to choose the best paths and avoid congested areas.

Conflict of interest between agents occurs when the routes or actions of individual agents overlap or contradict each other. It can lead to traffic conflicts, increased travel time, and congestion. These problems are solved by optimizing a general function that allows us to find a compromise between the interests of different agents, ensuring the efficient use of road infrastructure without creating conflicts:

$$\min_{A(a_i)} F_{opt}(S_E),$$

subject to the condition (5)

$$A(a_i) \cap A(a_j) = \varnothing \forall_{i \neq j}.$$

Using a mathematical approach to analyze and optimize the interaction of agents in multi-agent systems, especially in the context of complex dynamic systems such as traffic management in central districts of the city, is an essential component of the development of intelligent systems. Mathematical models allow identifying optimal behavioral strategies for individual agents and ensure consistency and coordination of their actions to achieve common goals, such as minimizing travel time, reducing the number of accidents, and improving the environmental situation in the city.

Evaluation of the impact of agents' actions on traffic capacity is based on an analytical approach to determining total travel time, delays, and other indicators of transport system efficiency. The use of weighting coefficients allows for considering different performance evaluation criteria, which makes it possible to balance the needs of travel speed and overall road safety.

The algorithm for improving traffic organization through the interaction of agents and the environment is shown in Fig. 4. Intelligent agent systems generate various scenarios of traffic situations using artificial intelligence to optimize traffic and congestion in the transport network in central districts of the city. Considering the characteristics and behavior of agents, they select the best scenario of events to increase highway capacity and reduce congestion.

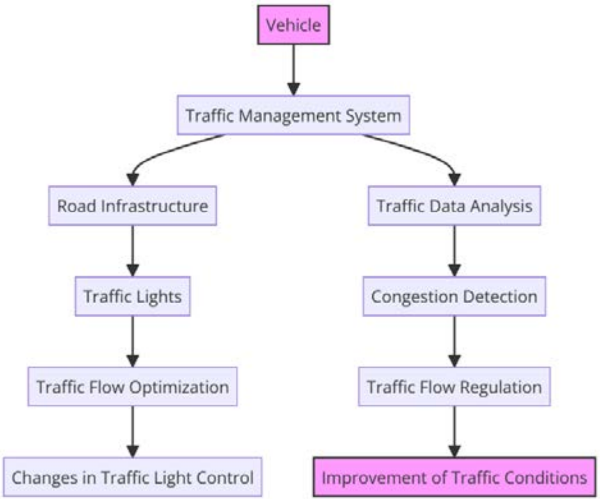

Fig. 4. Scheme of interaction of model elements for optimization of traffic and traffic flows

Using mathematical formulas and functions to describe the states and actions of agents and the interaction between agents and the environment, allows for accurate modeling and analysis of the system. It, in turn, contributes to developing effective management and optimization strategies for an information system for monitoring and organizing traffic in urban environments.

A model of traffic flow organization in the central parts of the city was developed using the theoretical tabs described above. A practical simulation of the multi-agent model was carried out using the AnyLogic program, which allows for combining technological innovations and theoretical approaches to modeling. As a part of the central district of Kyiv, the traffic on L. Ukrainka Boulevard was researched.

At the initial stage, Google Earth provided a visual basis for scaling and integrating the image into AnyLogic. It made it possible to accurately recreate the site`s geometry, including road surfaces, pedestrian areas, and other infrastructure elements

A comprehensive multi-agent model was created using the tools of various AnyLogic libraries, from the space allocation library to the agent-based modeling library. These tools made it possible to reproduce important aspects of the urban environment, including the road network, traffic, and various types of vehicles that act as independent agents with their own rules of behavior (Fig. 5).

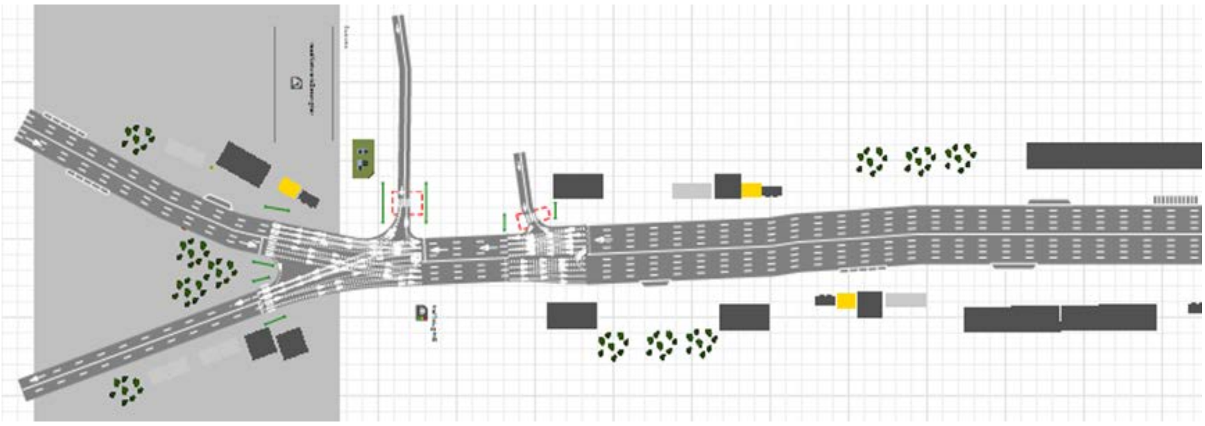

Fig. 5. An example of visualization on one sections of L. Ukrainka Boulevard in the AnyLogic program

The traffic library played an essential role in configuring the movement parameters of the agents, including the direction, speed, traffic flow volume, and endpoints of their activities. It provided the ability to analyze traffic flows in detail and identify potential safety problem areas.

Process modeling and agent-based modeling complemented the scenario, allowing us to add agents with various functions to the system and to recreate the dynamics of urban traffic, taking into account real-life data on public transport routes and the main flows of urban mobility.

An essential aspect of the implementation was the creation of traffic flow rules that control the agents` behavior based on official traffic rules and specific road surface conditions on L. Ukrainka Blvd. The composition of the traffic flow included public, individual, freight, motorcycle, and bicycle transport. For each type of vehicle, rules for their interaction were developed on different sections of the road network of the experimental boulevard. It provided the model with a high level of adequacy and the ability to be used to predict the impact of various factors on the safety and efficiency of traffic flow.

Running the model and analyzing the results revealed potential problems and provided important insights for urban infrastructure planning and traffic optimization. This multi-agent model has become a bridge between theoretical knowledge and practical application, opening new perspectives for understanding and improving urban transportation systems (Fig. 6).

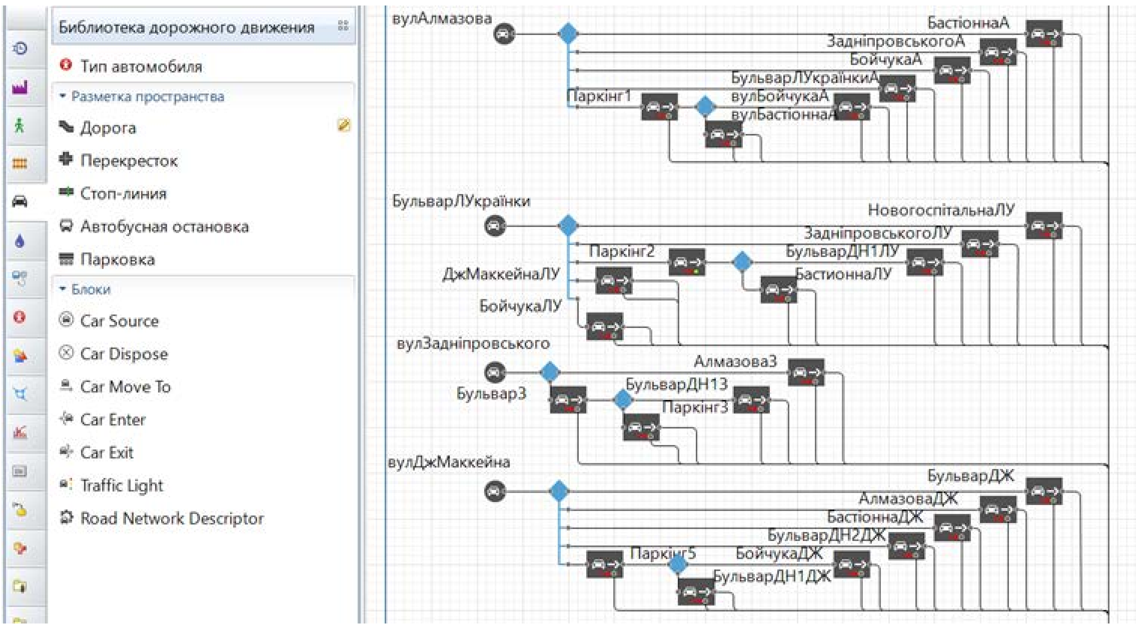

Fig. 6. Agent primitives for the formation of TP functioning rules and an example of their representation for different agents

The analysis of the road network of L. Ukrainka Boulevard based on field observations showed that the study object contains 13 critical points. During hours with high volumes, this leads to traffic complications and congestion. Calculations of field observations showed that this situation has a negative impact on the environment and causes an increase in the accident rate. Based on the simulation model, a study was conducted to reduce critical points and quantitative indicators of possible collisions and accidents, which contributed to improving road traffic (Table 3, 4).

Table 3

Traffic volume at the intersection during the day (based on field observations)

Hours of the day	Traffic volume									
	1	2	3	4	5	6	7	8	9	10
1	5	5	2	13	14	2	8	13	2	10
2	19	4	1	12	18	2	2	3	5	11
3	22	10	4	13	16	12	10	11	4	12
4	14	7	7	14	39	18	7	12	22	26
5	22	13	7	18	30	25	13	17	30	24
6	39	10	13	77	25	35	12	23	49	42
7	106	72	25	131	82	87	50	50	71	77
8	218	84	54	149	124	127	71	71	132	93
9	368	229	75	207	162	132	127	118	168	105
10	480	188	105	272	212	117	118	129	140	94
11	541	172	155	234	261	197	162	152	116	119
12	562	126	210	201	184	207	224	166	180	122
13	497	111	246	158	154	206	198	191	192	128
14	445	79	207	159	227	185	224	235	217	149
15	430	111	187	168	201	158	236	213	208	130
16	433	119	208	213	190	134	258	235	224	132
17	434	107	264	231	203	204	279	295	239	150
18	482	129	399	202	238	239	214	283	351	127
19	587	184	259	130	276	260	181	190	348	104
20	520	174	169	94	193	195	145	128	322	81
21	373	126	94	61	132	105	107	100	254	58
22	270	63	47	26	56	74	40	67	132	70
23	135	38	16	14	21	28	28	31	116	34
24	56	7	8	7	6	8	7	20	40	17
The sum	7058	2168	2762	2804	3064	2757	2721	2753	3562	1915

Table 4

Traffic volume at the intersection during the day (by using a simulation model)

Hours of the day	Traffic volume									
	1	2	3	4	5	6	7	8	9	10
1	2	3	4	5	6	7	8	9	10	11
1	3	1	1	7	5	1	5	8	1	8
2	7	2	1	4	3	1	1	1	2	5
3	8	6	2	9	8	5	4	5	2	9
4	9	2	2	8	13	11	4	6	15	10
5	10	5	2	11	19	14	6	5	22	16
6	37	7	11	53	11	23	6	16	34	23
7	96	66	16	119	63	56	27	31	65	49

Table continuation 4

1	2	3	4	5	6	7	8	9	10	11
8	198	68	35	121	119	98	59	58	102	68
9	310	167	59	180	141	115	110	112	123	60
10	400	171	89	237	184	102	103	120	138	68
11	460	145	107	204	227	171	141	134	114	98
12	500	100	179	175	160	180	195	154	165	102
13	429	101	206	137	134	179	172	178	159	118
14	441	87	199	138	197	161	195	220	199	125
15	400	98	168	146	175	137	205	201	200	109
16	409	103	208	185	165	117	224	209	204	113
17	413	99	245	201	177	177	243	256	213	142
18	450	109	350	176	207	208	186	260	254	122
19	499	150	231	113	240	226	157	178	279	65
20	465	147	145	82	168	170	126	113	230	34
21	278	104	67	53	115	91	93	67	121	30
22	178	44	39	23	49	64	35	32	34	22
23	87	25	11	10	15	11	11	19	21	12
24	10	7	3	5	2	3	3	11	24	6
The sum	7058	2168	2762	2804	3064	2757	2721	2753	3562	1915

Diagrams of the dynamics of changes in the accident rate in real-life conditions and according to the simulation model using multi-agent modeling methods were constructed based on the calculations. The graphical visualization of the results shows that the simulation model can be used to identify the most critical sections and sections whose modernization will improve the efficiency of traffic management (Fig. 7, 8). Such optimization can predictably lead to a reduction in the accident rate by 28–32 % and will help improve the situation on highways in the cities.

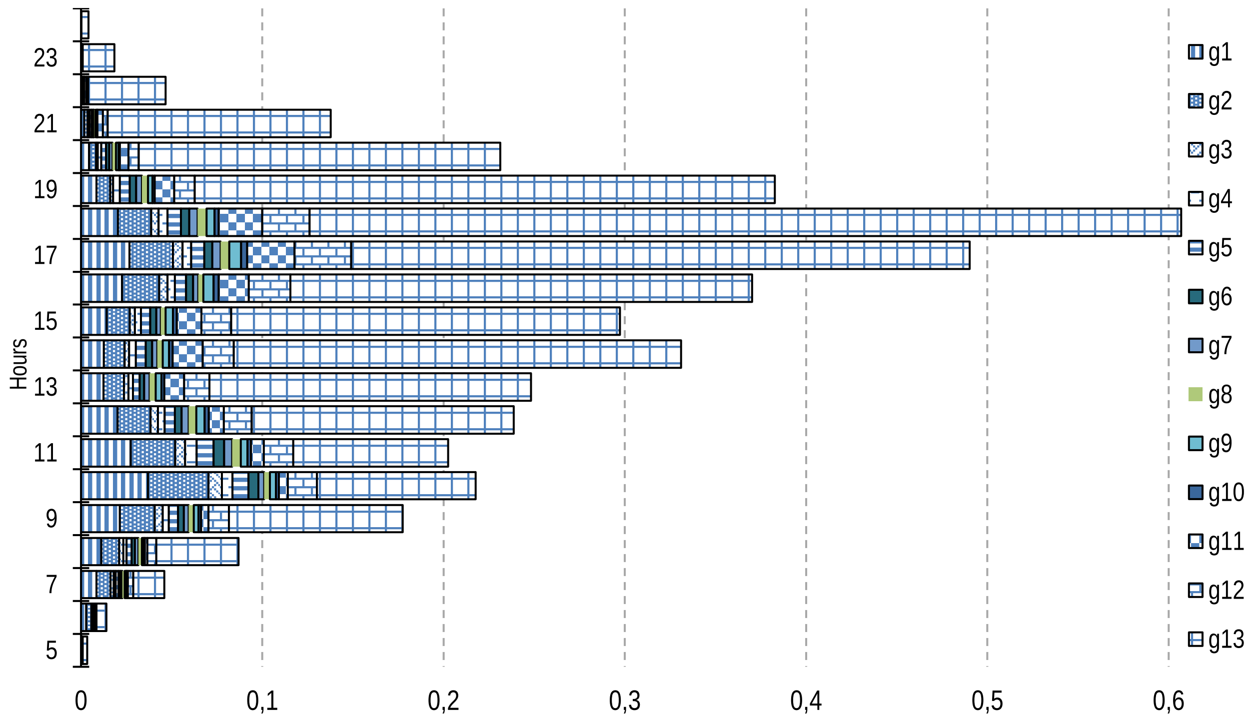

Fig. 7. Degree of danger of conflict points at the intersection (based on field observations)

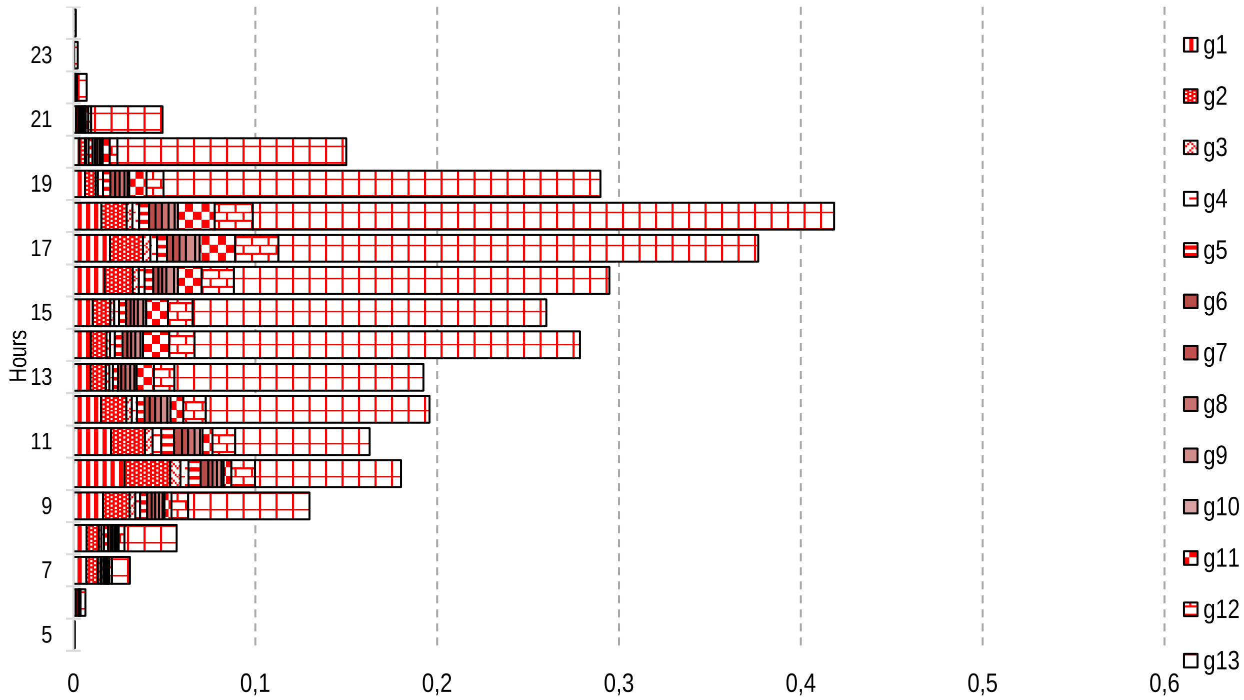

Fig. 8. Degree of danger of conflict points at the intersection (by using a simulation model)

The practical simulation of a multi-agent traffic model in the central areas of the city, conducted using AnyLogic software, demonstrates the significant potential of this approach to improve traffic management and the ability to adapt to different scenarios. It allows us to assess the effectiveness of potential traffic management measures in different conditions. The choice of L. Ukrainka Boulevard in Kyiv as the object of study provided a realistic basis for analyzing and testing the model in conditions as close to real life as possible.

Thus, multi-agent modeling becomes the foundation for developing modern intelligent urban transport network management systems that can ensure harmonious interaction between all road users, reducing congestion, reducing travel time, and improving the environmental situation in urban areas

5. CONCLUSIONS

The systematic application of the model not only improves the traffic situation in the short term by optimizing current traffic flows but also helps city planners and engineers make informed decisions about the development of transport infrastructure in the long term. A primary aspect of the system's effectiveness is its ability to scale and adaptability. The multi-agent approach makes it easy to integrate new agents (vehicles, traffic lights, sensors, et cetera) and services without a significant redesign of the entire system. The adaptability of the model is ensured by using machine learning and artificial intelligence algorithms that allow the system to “learn” from historical data and improve its traffic management algorithms.

One of the essential areas of system development is the introduction of predictive models that can analyze trends and predict changes in traffic, allowing for proactive management instead of reactive.

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МУЛЬТИАГЕНТНЕ МОДЕЛЮВАННЯ ОРГАНІЗАЦІЇ ДОРОЖНЬОГО РУХУ В МІСЬКИХ АГЛОМЕРАЦІЯХ

Анотація. *Розглянуто особливості мультиагентного моделювання для оптимізації дорожнього руху в центральних районах міст. Оцінюючи унікальні виклики, пов'язані з високою концентрацією транспорту, пішоходів та історичної забудови, досліджено потенціал мультиагентних систем для ефективного вирішення проблеми заторів, безпеки та якості життя у міських умовах. Потенціал мультиагентного моделювання в контексті управління дорожнім рухом у центральних районах міста дає змогу визначити ключові виклики та можливості. Багато науковців звертаються до основних аспектів такого моделювання і використовують їх у транспортно-дорожній галузі. Огляд сучасних досліджень* *та розробок показав, що мультиагентні моделі мають на меті імітувати та оптимізувати нагляд і контроль перевезень у різних сценаріях руху. Моделювання організації дорожнього руху в центральних районах міст є одним із ключових елементів планування міського розвитку та управління. Унаслідок зростання населення міст та збільшення кількості транспортних засобів проблеми заторів, забруднення повітря та неефективного використання інфраструктури стають дедалі актуальнішими. Тому можна зазначити, що мультиагентне моделювання організації дорожнього руху відкриває нові перспективи для розроблення ефективних стратегій управління транспортними потоками, забезпечуючи гнучке та адаптивне вирішення цих проблем. Проаналізовано використовувані підходи, визначено ключові компоненти системи і на основі математичного опису розроблено модель, яка демонструє взаємодію між агентами і середовищем. Практична симуляція моделі, виконана із використанням програмного забезпечення AnyLogic на прикладі бульвару Лесі Українки в м. Києві, підтверджує ефективність мультиагентного підходу. Результати дослідження вказують на можливість застосування розробленої моделі для вдосконалення інтелектуальних інформаційних систем управління транспортним потоком, що відкриває нові перспективи для покращення дорожнього руху в центральних районах міст.*

Ключові слова: *мультиагентне моделювання; дорожній рух; інформаційні системи; оптимізація; транспортний потік; AnyLogic; агент; математична модель; інтелектуальні системи.*