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MODEL OF THE TRAFFIC FLOW MANAGEMENT SYSTEM OF TWO INTERCONNECTED INTERSECTIONS

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The article presents the development of a model of a traffic flow control system for two consecutively located controlled intersections of an urban street and road network based on a discrete-cellular approach. The study is aimed at ensuring such a control mode in which a formed group of vehicles approaching the first intersection, after turning on the permitted signal, can overcome the second intersection without stopping also at the permitted signal. The model takes into account the width of the intersections, the distance between them, the number of vehicles in the group, their speed of movement and the logic of changing traffic light phases. The time dependencies for each vehicle within the group are analyzed and generalized formulas for determining the durations of the permitted and prohibited phases for both intersections are obtained. The proposed approach allows one to determine traffic light cycles in such a way as to avoid delays and excessive accumulation of vehicles at the second intersection, which is especially important in conditions of urban traffic flows with high intensity. The use of a cellular model allows one to visually reproduce the movement of cars, monitor their positions at any given time, and assess the impact of regulation parameters on the overall throughput. The developed model can be used to optimize the operation of controlled intersections, set fixed traffic light modes, and also as a basis for creating more complex adaptive control systems. The results obtained are practically significant for designing transport schemes, improving road infrastructure, and reducing congestion in the urban environment.
Key words: *traffic flow; road traffic; intersection; traffic flow control system; traffic signal; intersection capacity; transport network.*

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Introduction. Traffic light control systems are usually divided into two main types: systems with fixed parameters (so-called "hard" control) and adaptive systems that can change their modes depending on the current traffic situation.

Rigid control involves operating traffic lights on a predetermined cycle. The signals are switched at constant time intervals, without taking into account actual traffic volume or other dynamic factors (e.g., diurnal traffic fluctuations). This approach is typically used at intersections with predictable and relatively steady traffic flow.

Intelligent (adaptive) control, on the contrary, is capable of changing the duration of the phases in real time. For this purpose, various types of sensors are used – video cameras, induction loops, acoustic sensors and other devices that monitor traffic and pedestrian flows. The obtained data are processed by optimization algorithms that form the most efficient time structure of the traffic light cycle.

Compared to traditional systems, adaptive solutions provide a number of advantages:

Increased throughput: Flexible phase settings reduce latency and reduce the likelihood of congestion.

Rational use of energy. Optimizing traffic light operating modes during periods of light traffic helps reduce energy consumption.

Quick response to changes. The system quickly adjusts modes when traffic intensity changes, making control more efficient and stable.

Thus, adaptive traffic light systems are a more modern and effective traffic management tool, especially in conditions of heavy urban traffic and a complex network of intersections.

One of the problems of urban intersections in the case of tight control is such a parameter as the number of vehicles that manage to pass during the time of the permitted traffic light signal. This parameter is important for the efficiency of the traffic light. This parameter can be critical in urban conditions, where a large number of cars can create traffic jams if the time devoted to traffic is insufficient to allocate all vehicles.

With tight traffic light management, it is important to ensure that the time allocated to traffic is sufficient to avoid congestion and ensure smooth traffic flow. This may require careful adjustment of traffic light cycle times, taking into account peak loads and interactions with other traffic lights on the route.

Therefore, the development and implementation of traffic flow management systems at intersections that allow for the number of vehicles that can pass during the permitted time of the traffic light signal is an important task. Balanced traffic light management allows for optimizing traffic flow in the city, reducing carbon emissions and waiting times, contributing to the overall efficiency of the transport infrastructure.

Analysis of recent achievements and publications. Recent studies on traffic light control show a gradual shift from classical methods with rigid regulation to adaptive and intelligent approaches. Some works take into account the impact of external factors, such as vehicle emissions, on the urban environment [1]. However, they do not provide specific solutions for organizing continuous movement of groups of vehicles through several interconnected intersections, which limits their practical effectiveness.

Classical models with fixed parameters of traffic lights [2, 3] are used as basic optimization tools, but their effectiveness is limited in variable traffic flows and peak loads. They do not take into account the accumulation of vehicles at subsequent intersections and do not allow for precise control of the movement of a specific group of vehicles.

Systems based on simulations and intelligent controllers [4] allow for the evaluation of different control strategies under controlled conditions but are mostly tested in simulations or limited scenarios. Adaptive control methods using reinforcement learning [5, 6 and 10] make it possible to take into account the relationships between intersections and optimize flows, but they rarely provide accurate control of a specific group of cars and do not reproduce the visual position of cars at each moment in time.

Multi-agent and deep models [7–9] allow for the coordination of intersections on a network scale, but their testing is mostly limited to simulations, which reduces practical effectiveness in specific urban conditions. Review works [11, 12] emphasize the problems of scaling and integrating new approaches into real control systems.

It is these limitations that justify the need to create a model that allows synchronizing the phases of traffic lights at two consecutive intersections, ensuring continuous movement of formed groups of cars and increasing the throughput of the transport system.

Goal and problem statement. The purpose of this work is to create such a model of a traffic light control system for a system of two regulated intersections located one after the other, which allows a fixed group of cars from the traffic flow approaching the first intersection, after turning on the permitted traffic light signal at this intersection, to cross it at the permitted signal when moving to the second intersection.

Presentation of the main research material. To build the specified model, we will use a discrete-cell model of the transport network [13–15]. A similar approach can be attributed to a type of cellular automata (CA) – Block-sequential CA (or partitioned CA), in which the updating of cell states occurs in portions and sequentially in blocks. The essence of this approach is to cover the transport network with cells that can take two states, which are indicated by either black or white coloring of the cell and mean, respectively, that a car is located in this cell or there is none.

Movement through the network occurs by conditional “jumping” of cars from a cell to a neighboring cell, which is indicated by the corresponding coloring. Moreover, it should be noted that movement is possible only in free cells, that is, if it is necessary to move a certain car to a certain cell, then if it is black, you should wait until it becomes white and only after that it will be possible to carry out the movement itself.

This rule ensures that conflicts between vehicles are avoided and allows the model to reproduce basic patterns of traffic flow behavior.

Consider a transport network that is a system of two intersections located one after the other, each of which we will call "intersection 1" and "intersection 2", respectively. Such a configuration is typical for urban street networks, where closely spaced intersections often significantly influence each other due to the propagation of queues and changes in signal phases.

On the main approach to intersection 1, consider a group of cars of a fixed number, assuming that their arrival rate remains constant during the observation period, which allows us to analyze traffic dynamics under controlled and repeatable conditions.

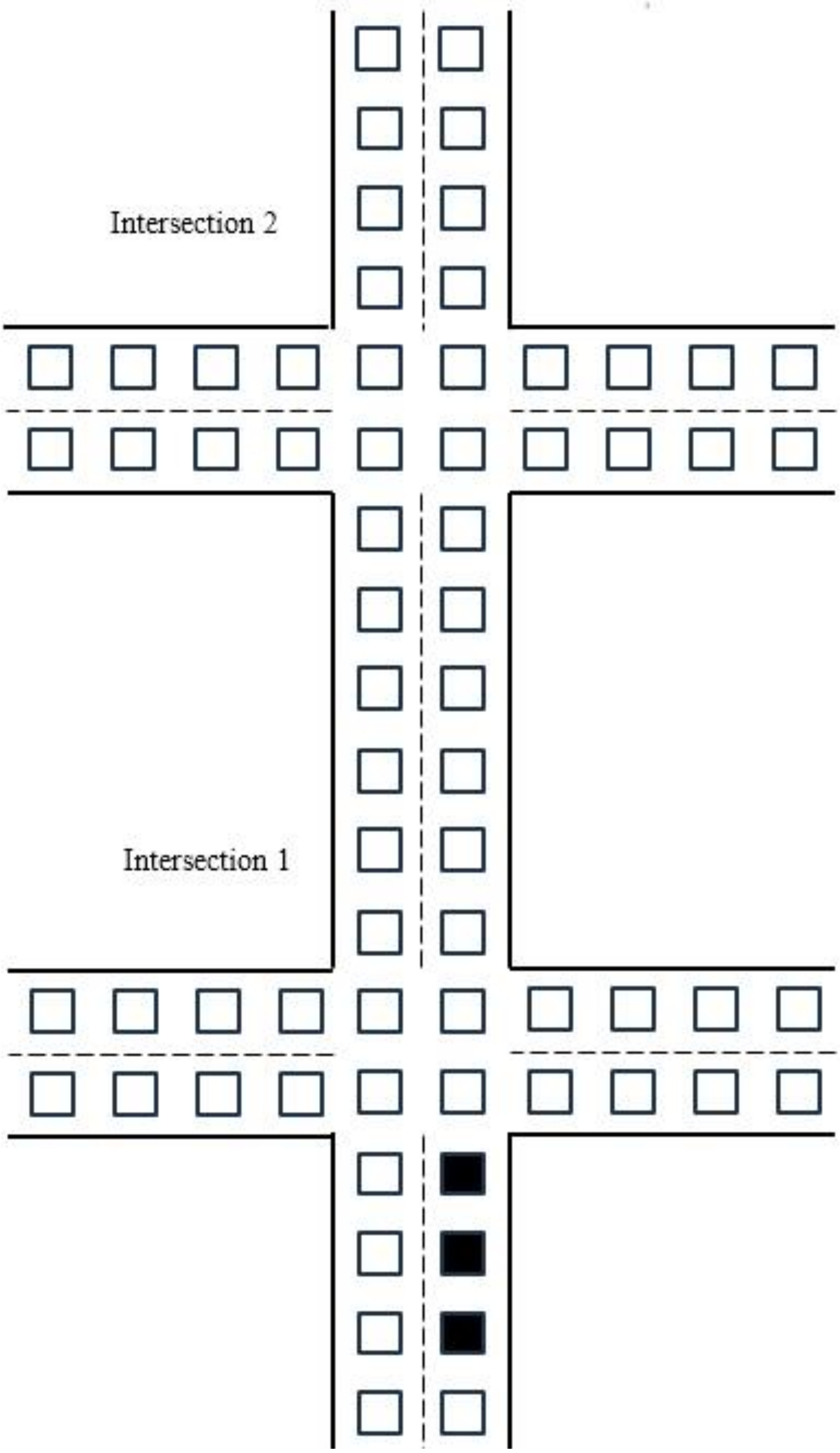


Figure 1 – Cellular model of a transport network with two intersections, located one after another

The control process begins at some initial moment in time. Let us assume that at this moment the specified group of cars is already located on the approach.

Let us assume that both intersections are equipped with traffic lights operating in two-phase modes.

For the convenience of further discussion, we will consider only the durations of traffic light phases without dividing them into main and intermediate cycles. If for practical application it is necessary to establish specific cycle values, then it will be necessary to subtract the corresponding recommended fixed values of intermediate cycles from the phase duration values to obtain the values of the durations of the main cycles.

Let us introduce the necessary input parameters of the model, which are shown in Table 1.

Table 1 – Model parameters

№	*Designation parameter*	*Parameter name*	*Unit measurement parameter*
Model input parameters			
1	t_0	Initial time	units of time
2	k	Number of cars in the group	units
3	T_C^1	Duration of the first intersection cycle	units of time
4	T_{F1}^1	Duration of the first (permitted) phase the first intersection	units of time
5	T_{F2}^1	Duration of the second (forbidden) phase the first intersection	units of time
6	T_C^2	Cycle duration of the second intersection	units of time
7	T_{F1}^2	Duration of the first (forbidden) phase second intersection	units of time
8	T_{F2}^2	Duration of the second (permitted) phase second intersection	units of time
9	L_{1-2}	Distance (in cells) between intersections	units
10	S_p	Width of each intersection (in cells)	units
11	Δt	The time it takes for one car to move from one cell to the next	units of time

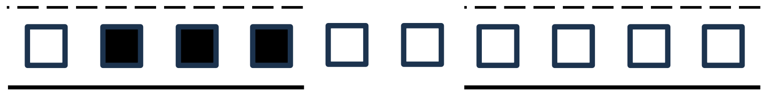
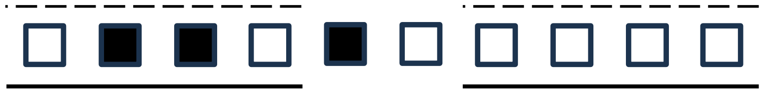
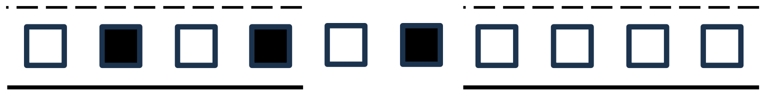
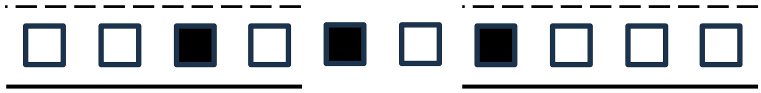
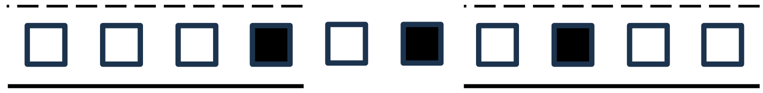
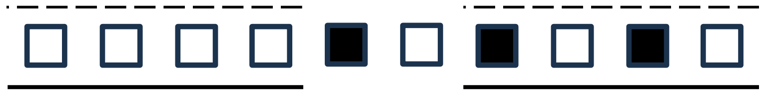
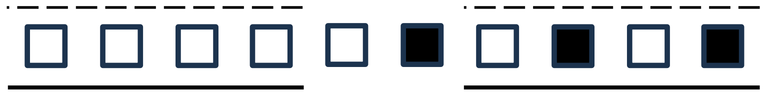
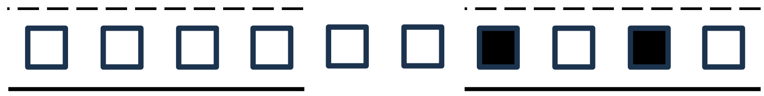
Since, as it was established, at the initial moment of time at the first intersection the permitted signal for the forward direction is turned on, then at the same time at the second intersection the prohibited signal for the same direction should be turned on. And it will work until the first car from the group reaches the second intersection.

Let's find how long it takes from the start of the countdown to turn on the permitted signal at the second intersection, in other words, let's find the duration of the prohibited phase of intersection 2:

$$T_{F1}^2 = \left(S_p + L_{1-2}\right) \cdot \Delta t \,.$$

Next, we determine the duration of the allowed phase of the first intersection – it is equal to the time it takes for the last car in the group to leave intersection 1. To obtain this value, we create a schematic table that clearly shows the change in the position of the cars and the corresponding time spent on this. Let us consider the case when $S_p = 2$.

Table 2 – Change in the position of cars on the network and the corresponding time spent it's time in the case of $S_p=2$

№	***Position of cars on a fragment of the transport network***	***Time to reach position***
1		0
2		Δt
3		$2\Delta t$
4		$3\Delta t$
5		$4\Delta t$
6		$5\Delta t$
7		$6\Delta t$
8		$7\Delta t$

As can be seen from Table 2, for one car the time to leave the intersection zone 1 in the case of $S_p=2$ is $3\Delta t$, for the second car $5\Delta t$, for the third – $7\Delta t$. Reasoning similarly, it is clear that for *the* k-th car this time will be $(2k+1)\Delta t$.

Let us find similar quantities at $S_p=3$. They will be respectively:

$$\begin{cases} 1 \to 4\Delta t \\ 2 \to 6\Delta t \\ 3 \to 8\Delta t \\ \dots \\ k \to (2k+2)\cdot\Delta t \end{cases}.$$

Then, for an arbitrary value of the intersection width S_p, these values will be respectively equal to:

$$\begin{cases} 1 \to (S_p+1)\cdot\Delta t \\ 2 \to (S_p+3)\cdot\Delta t \\ 3 \to (S_p+5)\cdot\Delta t \\ \dots \\ k \to (S_p+2k-1)\cdot\Delta t \end{cases}.$$

Therefore, the duration of the allowed phase of intersection 1 is:

$$T_{F1}^{1} = (S_p+2k-1)\cdot\Delta t.$$

Next, we will determine the duration of the permitted phase of intersection 2. It will be equal to the time it takes for the last k – th car of the group to leave the intersection zone 2. This value conventionally consists of two parts, the first of which is equal to the time it takes for the *k-th* car to cover the distance from its current location on the network at the moment when the permitted phase of intersection 2 begins to operate, and the time it takes to cover the zone of intersection 2 itself.

To find out the position of the *k-th* car of the group in the system, we will perform inductive reasoning.

If *k =1* , then it is obvious that the duration of the permitted phase of intersection 2 is equal to the time the car leaves the intersection zone, i.e.:

$$T_{F2}^{2}|_{k=1} = \left(S_p + 1\right) \cdot \Delta t.$$

For *k = 2* we get:

$$T_{F2}^{2}|_{k=2} = \left(S_p + 3\right) \cdot \Delta t.$$

At *k =3* we have:

$$T_{F2}^{2}|_{k=3} = \left(S_p + 5\right) \cdot \Delta t.$$

Then for an arbitrary value of k the duration of the allowed phase of intersection 2 will be determined by the expression:

$$T_{F2}^{2} = \left(S_p + 2k - 1\right) \cdot \Delta t.$$

Then the complete traffic light cycle for intersection 2 is:

$$T_C^2 = T_{F1}^2 + T_{F2}^2 =$$

$$= \left(S_p + L_{1-2}\right) \cdot \Delta t + \left(S_p + 2k - 1\right) \cdot \Delta t =$$

$$= \left(2S_p + L_{1-2} + 2k - 1\right) \cdot \Delta t.$$

Considering that for the coordinated operation of the system of two intersections, it is necessary to fulfill the following condition:

$$T_C^1 = T_C^2.$$

Then, the complete traffic light cycle for intersection 1 will be determined using the system:

$$\begin{cases} T_{F1}^1 = T_{F2}^2 = \left(S_p + 2k - 1\right) \cdot \Delta t \\ T_{F2}^1 = T_{F1}^2 = \left(S_p + L_{1-2}\right) \cdot \Delta t \\ T_C^1 = T_{F1}^1 + T_{F2}^1 = \left(S_p + 2k - 1\right) \cdot \Delta t + \left(S_p + L_{1-2}\right) \cdot \Delta t = \\ = \left(2S_p + L_{1-2} + 2k - 1\right) \cdot \Delta t\,. \end{cases}$$

Let us consider a numerical example of the application of the proposed model.

Let the studied intersection system have the following input characteristics:

1) the length between intersections is – 1000 m;
2) the width of the intersection is – 35 m;
3) the dynamic dimension of vehicles in aggregate units is – 4 m;
4) the average speed of cars is – 45 km/h;
5) the number of cars in the group is – 20.

To apply the model, it is necessary to transform the input parameters to the parameters specified in Table 1. The results of the transformations are presented in Table 3.

Table 3 – Model input parameters

№	*Designation parameter*	*Value*	*Unit measurement parameter*
Model input parameters			
1	k	20	units
2	L_{1-2}	=1000/4=250	units
3	S_p	=[35/4]+1=9	units
4	Δt	=(5/45)*3,6=0,4	sec

Let's calculate the values of the durations of phases and traffic light cycles using the formulas above:

$$\begin{cases} \begin{cases} T_{F1}^1 = [(9 + 2 \cdot 20 - 1) \cdot 0{,}4] + 1 = 20 \text{ (sec)} \\ T_{F2}^1 = [(9 + 250) \cdot 0{,}4] + 1 = 104 \text{ (sec)} \\ T_C^1 = T_{F1}^1 + T_{F2}^1 = 20 + 104 = 124 \text{ (sec)} \end{cases} \\ \begin{cases} T_{F1}^2 = T_{F2}^1 = 104 \text{ (sec)} \\ T_{F2}^2 = T_{F1}^1 = 20 \text{ (sec)} \\ T_C^2 = T_{F1}^1 + T_{F2}^1 = 104 + 20 = 124 \text{ (sec)} \end{cases} \end{cases} .$$

The results of the calculations are presented in the form of Table 4.

Table 4 – Model output parameters

№	*Designation parameter*	*Value*	*Unit measurement parameter*
Model output parameters			
1	T_C^1	124	sec
2	T_{F1}^1	20	sec
3	T_{F2}^1	104	sec
4	T_C^2	124	sec
5	T_{F1}^2	104	sec
6	T_{F2}^2	20	sec

Conclusions. Thus, the paper proposes the development of a traffic flow control system model for two interconnected controlled intersections, based on a discrete- cell description of the transport network. Formulas for determining the duration of traffic light phases at each intersection depending on the number of vehicles in the group, the width of the intersections, the travel time between cells and the distance between the intersections are obtained. It is shown that by means of phase synchronization it is possible to ensure the unhindered passage of the formed group of vehicles through the second intersection without waiting, which allows to increase the throughput and reduce the volume of queue accumulation. The proposed model is suitable for use in urban traffic conditions and can serve as the basis for further improvement of traffic light control systems within the framework of both rigid and adaptive control.

Prospects for further research. Further research can be aimed at expanding the model by taking into account the variable intensity of the traffic flow, stochastic traffic parameters and the non-constant structure of groups of cars. It is also relevant to apply the model in conditions of multi-lane traffic, the presence of turning flows and different traffic light operating programs. A promising direction is the integration of the discrete- cell model with adaptive control algorithms based on data from sensors or video surveillance to ensure automatic adjustment of the duration of phases in real time. In addition, it is advisable to develop software for modeling the operation of a group of interconnected intersections and conduct a comparative analysis of the effectiveness of synchronized modes in real urban conditions.

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Славич В. П., Волошанський В. О. МОДЕЛЬ СИСТЕМИ УПРАВЛІННЯ ТРАНСПОРТНИМ ПОТОКОМ ДВОХ ВЗАЄМОПОВ'ЯЗАНИХ ПЕРЕХРЕСТЬ

У статті представлено розробку моделі системи управління транспортним потоком для двох послідовно розташованих регульованих перехресть міської вулично-дорожньої мережі на основі дискретно-клітинкового підходу. Дослідження спрямоване на забезпечення такого режиму управління, за якого сформована група транспортних засобів, що знаходиться на підході до першого перехрестя, після ввімкнення дозволеного сигналу може без зупинок подолати друге перехрестя також на дозволений сигнал. Модель враховує ширину перехресть, відстань між ними, кількість автомобілів у групі, швидкість їх переміщення та логіку зміни світлофорних фаз. Проаналізовано часові залежності для кожного автомобіля всередині групи та отримано узагальнені формули визначення тривалостей дозволених і заборонених фаз для обох перехресть. Запропонований підхід дозволяє визначати світлофорні цикли так, щоб уникнути затримок та надмірного накопичення транспортних засобів на другому перехресті, що особливо важливо в умовах міських транспортних потоків із високою інтенсивністю. Використання клітинкової моделі дає змогу наочно відтворювати рух автомобілів, контролювати їх позиції в кожний момент часу та оцінювати вплив параметрів регулювання на загальну пропускну здатність.

Розроблена модель може бути використана для оптимізації роботи регульованих перехресть, налаштування фіксованих режимів світлофорів, а також як основа для створення більш складних адаптивних систем керування. Отримані результати є практично значущими для проєктування транспортних схем, удосконалення дорожньої інфраструктури та зменшення заторів у міському середовищі.

Ключові слова: *транспортний потік; дорожній рух; перехрестя; система управління транспортним потоком; світлофорна сигналізація; пропускна здатність перехрестя; транспортна мережа.*

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