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MODELING OF TRAFFIC IN INTELLIGENT TRANSPORTATION SYSTEMS

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Method of forming multiprogram control of an isolated intersection

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The simplest and most desirable method of traffic signal control is precalculated regulation, when the parameters of the traffic light object operation are calculated in advance and activated in accordance to a schedule. This work proposes a method of forming a signal plan that allows one to calculate the control programs and set the period of their activity. Preparation of initial data for the calculation includes the formation of a time series of daily traffic intensity with an interval of 15 minutes. When carrying out field studies, it is possible that part of the traffic intensity measurements is missing. To fill up the missing traffic intensity measurements, the spline interpolation method is used. The next step of the method is to calculate the daily set of signal plans. The work presents the interdependencies, which allow one to calculate the optimal durations of the control cycle and the permitting phase movement and to set the period of their activity. The present movement control systems have a limit on the number of control programs. To reduce the signal plans' number and to determine their activity period, the clusterization using the *k*-means method in the transport phase space is introduced In the new daily signal plan, the duration of the phases is determined by the coordinates of the received cluster centers, and the activity periods are set by the elements included in the cluster. Testing on a numerical illustration showed that, when the number of clusters is 10, the deviation of the optimal phase duration from the cluster centers does not exceed 2 seconds. To evaluate the effectiveness of the developed methodology, a real intersection with traffic light regulation was considered as an example. Based on field studies of traffic patterns and traffic demand, a microscopic model for the SUMO (Simulation of Urban Mobility) program was developed. The efficiency assessment is based on the transport losses estimated by the time spent on movement. Simulation modeling of the multiprogram control of traffic lights showed a 20% reduction in the delay time at the traffic light object in comparison with the single-program control. The proposed method allows automation of the process of calculating daily signal plans and setting the time of their activity.

Keywords: traffic light regulation, multiprogram control, time series, clustering, *k*-means

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МОДЕЛИРОВАНИЕ ТРАФИКА В ИНТЕЛЛЕКТУАЛЬНЫХ ТРАНСПОРТНЫХ СИСТЕМАХ

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Методика формирования многопрограммного управления изолированным перекрестком

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Наиболее простым и востребованным практикой методом управления светофорной сигнализацией является предрассчитанное регулирование, когда параметры работы светофорного объекта рассчитываются заранее и затем активируются согласно расписанию. В работе предложена методика формирования сигнального плана, позволяющая рассчитать программы регулирования и установить период их активности. Подготовка исходных данных для проведения расчета включает формирование временного ряда суточной интенсивности движения с интервалом 15 минут. При проведении полевых обследований возможно отсутствие части измерений интенсивности движения. Для восполнения недостающих значений предложено использование кубической сплайн-интерполяции временного ряда. Следующем шагом методики является расчет суточного набора сигнальных планов. В работе приведены зависимости, позволяющие рассчитать оптимальную длительность цикла регулирования и разрешающих движение фаз и установить период их активности. Существующие системы управления движением имеют ограничения на количество используемых программ регулирования. Для сокращения количества сигнальных планов и определения периода их активности используется кластеризация методом *k*-средних в пространстве длительности транспортных фаз. В новом суточном сигнальном плане длительность фаз определяется координатами полученных центров кластеров, а периоды активности устанавливаются элементами, вошедшими в кластер. Апробация на числовом примере показала, что при количестве кластеров 10 отклонение оптимальной длительности фаз от центров кластеров не превышает 2 с. Для проведения оценки эффективности разработанной методики на примере реального пересечения со светофорным регулированием. На основе натурных обследований схемы движения и транспортного спроса разработана микроскопическая модель для программы SUMO (Simulation of Urban Mobility). Оценка эффективности произведена на основе потерь транспорта, оцениваемых затратами времени на передвижение. Имитационное моделирование многопрограммного управления сигналами светофора показало снижение времени задержки (в сравнении с однопрограммным управлением) на 20 %. Предложенная методика позволяет автоматизировать процесс расчета суточных сигнальных планов и установки времени их активности.

Ключевые слова: светофорное регулирование, многопрограммное управление, временной ряд, кластеризация, *k*-средние

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1. Introduction

The simplest and most desirable method of traffic signal control is precalculated regulation, when the parameters of the traffic light object operation are calculated in advance and activated at the intersection by a timer [Vlasov, 2012]. This method of control is also called the time-dependent regulation. The advantages of this method of control include the following:

- easy and affordable implementation; it is enough to have a minimum set of equipment — road controller and traffic lights;
- quite a high efficiency in organizing regular surveys and updating control programs.

The main disadvantage of this control method is that it is impossible to adjust the operating mode automatically when the traffic intensity changes. In this case it is necessary to re-conduct the field studies and calculate a new signal plan.

From the point of view of the method of forming the signal plan, the issue of developing a phase-by-phase crossroad scheme and determining the duration of the phases of the control cycle is most fully studied [Webster, 1958; Shelkov, 1995]. Insufficient attention is paid to the issues of data preparation for calculating the signal plan and determining the activity time of the calculated control programs. From the perspective of optimal control, each control program should correspond to its own intensity value. Practically, it is usually limited to the use of two or three pre-calculated control programs during the active period of the day.

Yu. D. Shelkov [Shelkov, 1995] suggested using the traffic intensity graph to determine the activity time of control programs. The determination of the required number of control programs is designated based on the fact that, if the actual cycle duration deviates from the optimal one in the range of 25%, it does not lead to a significant increase in transport delay. The first program is recommended to be calculated for the traffic intensity corresponding to the peak hours of the day. To determine the moment of transition to the second program, the cycle time of the first program is reduced by 25%.

A. S. Kashtalinsky [Kashtalinsky et al., 2017] proposed a method for calculating the signal plan by dividing the period of the signal plan action into 15-minute intervals, followed by combining them into clusters. To solve the clustering issues, “the nearest neighbor” method was used. It is also known as the “single-link method”. The measure of objects' proximity was determined in the space of traffic intensity for groups of lanes. Using the traffic intensity values obtained, the control programs are recalculated.

The following disadvantages are typical for the above-mentioned methods:

- the allocation of the operating time of the control programs in the traffic intensity space does not allow one to take into account the phase duration restrictions used in the calculation;
- “the nearest neighbour” method used in [Kashtalinsky et al., 2017] does not guarantee combining intervals with similar traffic intensity values, but located at a significant time distance, into one control program. In this way, the required number of control programs unnaturally increases. This situation can make it difficult to use them in road controllers;
- hierarchical algorithms of clustering, which include “the nearest neighbor” method, tend to form “superclusters” that comprise most of the classification objects. In relation to the formation of the signal plan, this effect leads to its degradation to the level of single-program control.

2. Problem statement for multiprogram green time control

The problem of forming the signal plan is considered below using a specific intersection. Field studies' data of the intersection of the Izmailova street and Strelbishchenskaya street in Penza was available for this study. The data was obtained by camera processing of video recordings from 6 a.m. to 9 p.m. with an interval of one hour. The solution to the problem of calculating the daily signal plan is formulated in the statement [Webster, 1958; Shelkov, 1995]. The duration of the control cycle is determined by the formula

$$T = \frac{1.5 \cdot \sum_J t_j + 5}{1 - \sum_N Y_n}, \tag{1}$$

where T is the cycle duration, s; $\sum_J t_j$ is the sum of all phases whose duration is fixed (transition cycles, pedestrian phases, etc.), $j \in J$; Y_n are the phase coefficients of transport phases, $n \in N$; J is the set of phases whose duration is fixed; and N is the set of transport phases whose duration is to be determined.

The phase coefficients Y_n are determined by the following procedure. The phase coefficients y_k for each group of lanes are determined using the formula

$$y_k = \frac{q_k}{C_k}, \tag{2}$$

where q_k is the traffic intensity for a group of lanes, vph and C_k is the saturation flow for lane k, vph.

The determination of phase coefficients on a set $\hat{O}$ is as follows:

$$Y_n = \max(y_m), \quad m \in \hat{O} \wedge m \in n. \tag{3}$$

The duration of green signals for transport phases g_n is determined by the formula

$$g_n = \frac{\left(T - \sum_J t_j\right) \cdot Y_n}{\sum_N Y_n}. \tag{4}$$

The traffic scheme assumed the following order of movement:

- vehicles' pass on the Izmailova street (phase 1);
- pedestrians' pass in the selected phase with a duration of 14 s (phase 3);
- vehicles' pass on the Strelbishchenskaya street (phase 5);
- in phases 2, 4 and 6, intermediate cycles with a duration of 3 seconds are implemented.

The intensity was calculated in 15-minute intervals obtained by the cubic spline interpolation method of time series of traffic intensities for groups of lanes. The total number of control programs as a result of the calculation was 60. It should be noted that not all road controllers have the ability to use this number of programs. Usually their number is limited to 8.

To reduce the number of control programs, non-hierarchical clustering methods are considered for the reasons mentioned above. The K-means algorithm is the most popular. The method is based on minimizing the sum square deviation of cluster points from the centers of these clusters [Press et al., 2007; Vinnikov, Shalev-Shwartz, 2014; Amorim, Hennig, 2016]:

$$V = \sum_{i=1}^{k} \sum_{x \in S_i} (x - \mu_i)^2,$$

where k is the number of clusters, S_i id the resulting clusters, and μ_i is the center of mass of all x vectors from the S_i cluster.

At each iteration of the algorithm, the centre of mass for each cluster is calculated, which was obtained in the previous step, then the vectors are divided into clusters again according as which of the new centres was closer to the selected metric. The algorithm convergence condition assumes that there is no significant change in the intra-cluster distance at any iteration.

Compared to hierarchical methods, this method requires a hypothesis of the most likely number of clusters. In the case at hand, their number is limited and varies from 8 to 16 depending on the capabilities of the road controller.

Clusterization of control programs (Fig. 1) using the *k*-means method is performed with the scikit-learn machine learning package. Ten clusters were selected and the coordinates of cluster centers (centroids) were determined.

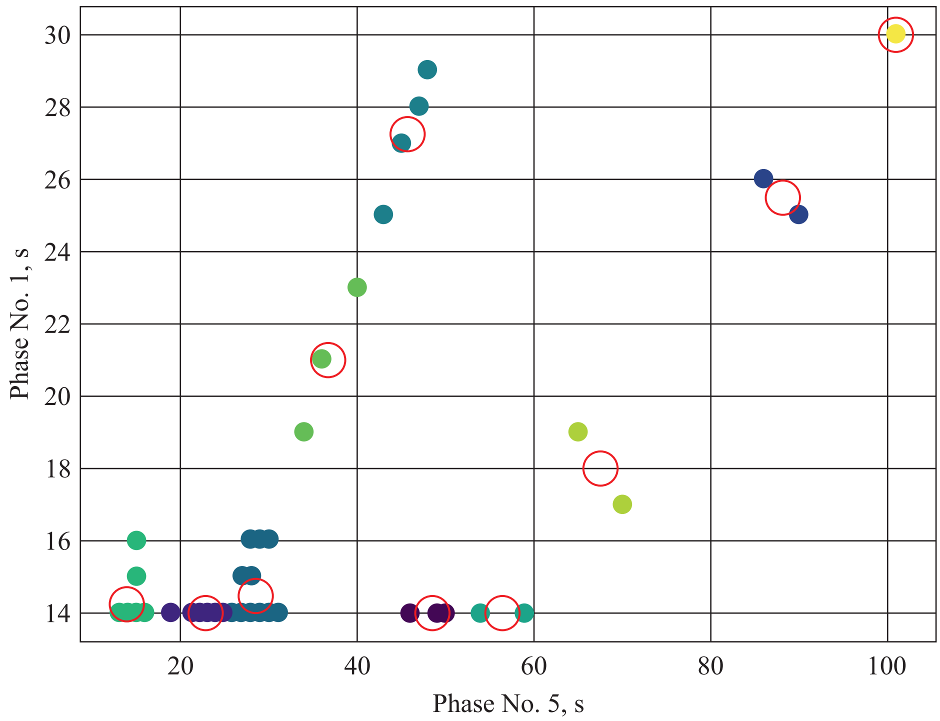

Fig. 1. Results of clusterization of traffic light control programs in the space of transport phases *Phase No. 1* and *Phase No. 5*

When the number of clusters is ten, the deviation of the optimal phase duration from the cluster centers (indicated by red circles) does not exceed 2 s for phase 5 and 3 s for phase 1. Thus, the quality of clustering in relation to the problem of forming a signal plan using the *k*-means method can be considered satisfactory.

In relation to the problem of forming daily signal plans, the coordinates of centroids determine the duration of transport phases of control programs (Table 1), and the indices of cluster objects determine the periods of their activity (Figure 2).

3. Simulation and efficiency assessment

The effectiveness of the given method of forming signal plans is evaluated below. The most accurate tool for evaluating solutions for the development of a transport system or control systems is the microscopic modelling [Vlasov, 2014; Vlasov, 2018].

Table 1. Duration of phases of the centroid signal plan

Program	Duration of phases, s						*T*
	1	2	3	4	5	6	
	Transport	Intermediate cycles	Pedestrian	Intermediate cycles	Transport	Intermediate cycles	
1	29	3	14	3	14	3	66
2	88	3	14	3	26	3	137
3	14	3	14	3	14	3	51
4	56	3	14	3	14	3	93
5	37	3	14	3	21	3	81
6	23	3	14	3	14	3	60
7	48	3	14	3	14	3	85
8	46	3	14	3	27	3	96
9	68	3	14	3	18	3	109
10	101	3	14	3	30	3	154

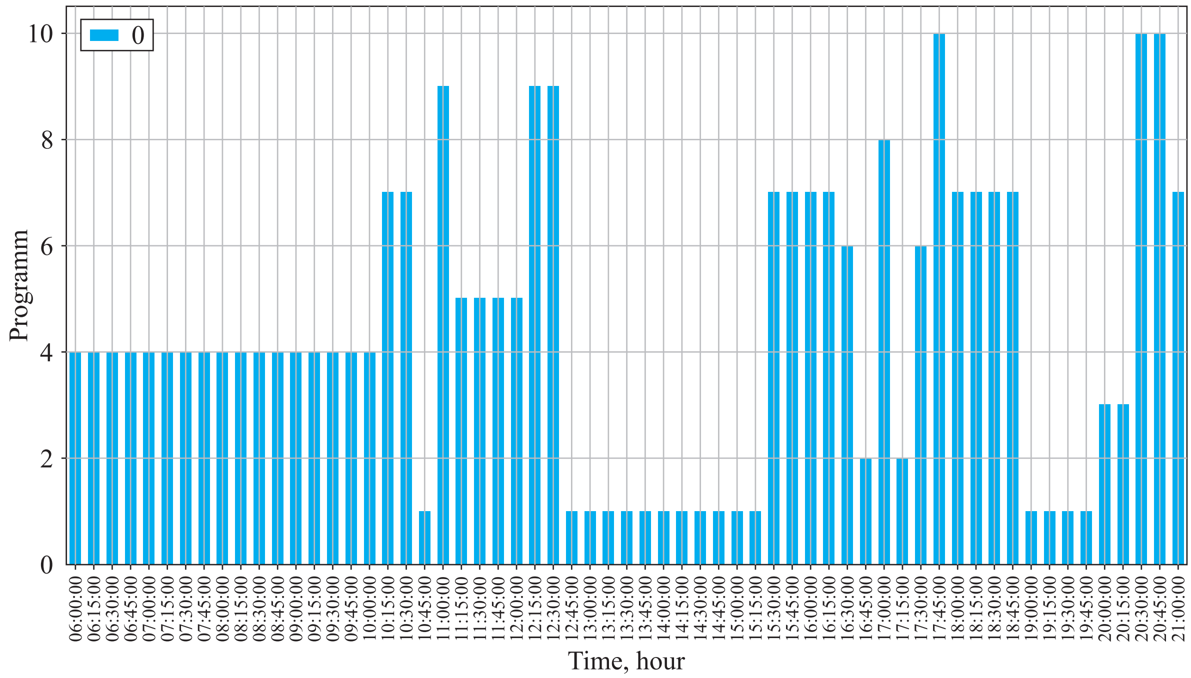

Figure 2. Activity periods of traffic light control programs obtained by the *k*-average method

The software SUMO (Simulation of Urban Mobility) is best suited to resolve research tasks [Krajzewicz, 2012]. This microscopic modeling program is spread under the EPL 2.0 license and is open source software.

Microscopic modeling consists of three stages: preparation of the transport network, traffic demand and simulation scenario; simulation by itself; and reporting and processing of results. To create the model correctly, the transport network and the geographical base were converted with the Open Street Map. Based on the field research conducted, the number of lanes and permitted traffic directions were determined using the NetEdit tool. Switching of control programs was implemented via their switching schedule WAUT:

```
<WAUT startProg="1" refTime="100" id="w1">
   <wautSwitch to="4" time="900"></wautSwitch>
   <wautSwitch to="7" time="15300"></wautSwitch>
…
   <wautSwitch to="9" time="22500"></wautSwitch>
   <wautSwitch to="1" time="24300"></wautSwitch>
</WAUT>
```

The creation of traffic demand was performed stochastically by the jtrrouter program based on field studies of traffic intensity. The initial data for generating traffic demand was the intensity at the entrances to the model and the proportion of turning flows at intersections.

Microscopic modeling reports are available in xml-files or can be transmitted via socket — the TraCI module's connection. Simulation results are presented both in an aggregated form for transport network elements and in a disaggregated form — the current state of modeling objects.

The effectiveness of traffic management methods or traffic light control systems is evaluated on the basis of transport losses estimated based on fuel consumption for movement or time spent on movement. Figure 3 shows a comparison of the waiting time for transport at a traffic light object with a single-program and a multiprogram control. The use of multiprogram control, calculated according to the proposed method, reduces the delay time at a traffic light object in comparison with single-program control by 20%.

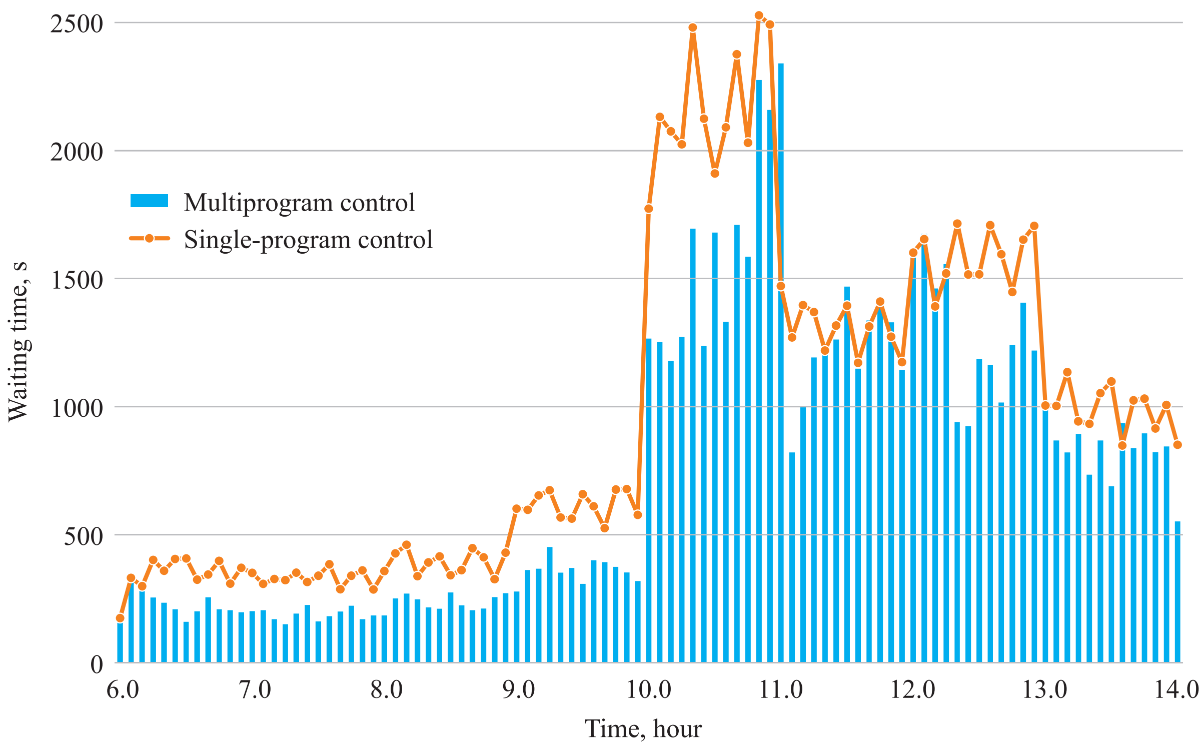

Figure 3. Time delay of transport with a single- and a multiprogram control on the way to the Izmailova street from the Antonova street in the period from 6: 00 to 14: 00

Conclusion

The method of forming a daily signal plan based on sampled field studies involves filling in the traffic intensity with 15-minute intervals by cubic spline interpolation, calculating the duration of the control cycle, followed by reducing the plan dimension by clustering by k-means in the space of transport phases. The process of calculating signal plans and setting the time of their activity is fully automated. The signal plan obtained by the described method fully covers the permitted values of the traffic light cycle elements, ensuring effective control of the traffic light object.

The presence of seasonal components in traffic demand and its overall growth due to the increase in the number of cars in the population requires additional research aimed at developing a methodology for determining the period of the calculated signal plans relevance.

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