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The Influence of the Stationarity Property on Traffic Flow Control

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ABSTRACT

This study provides an overview of traffic control methods using automated traffic control systems (ATCS). The main approach highlighted during the analysis is the application of rigid multi-program management, including a library of coordination programs. The study also found a dependence of the period of operation of each coordination program on the state and intensity of traffic flow (TF), noting an increase in the period of stationarity with an increase in the intensity of TF. Based on the system analysis, a mathematical dependence of the control parameter on the intensity affecting the efficiency of TF management is proposed. The results obtained can be applied to optimize the operation of the automated control system and develop effective traffic management strategies.

Introduction

The use of new technologies and the calculation of traffic control modes was studied in many research works. As a result, the main operating modes of the automated control system and calculations of traffic light control parameters were established in accordance with changes in the traffic characteristics of the TF (Braylovsky and Granovsky, 1975; Kapitanov and Khilazhev, 1985; Kremenets, 2005, Petrov, 2020).

A variety of strategies are used to optimize the use of road infrastructure. These approaches include the introduction of traffic restrictions in certain areas, access control to urban areas, the introduction of a toll system, the organization of paid parking and tougher penalties for violations of parking and stopping rules. In addition, improving public transport and creating comfortable conditions for its use are also important aspects of improving the efficiency of the transport system. All these measures are aimed at ensuring more efficient and sustainable use of urban infrastructure, which contributes to improving the quality of life of citizens and improving the environmental situation in the city (Mikhailov, 2014). The operation of the automated control system for 40 years has shown that not all parameters of traffic light regulation are clearly spelled out. The period of validity of one PC (program coordination) mode is mentioned indirectly in all works. This is due to the fact that the TF can be in one of 3 states (Petrov, 2020).

- free state,
- group state,
- bound state.

When transitioning from one TF state to another, the significance of its properties changes:

- stochasticity;
- stationarity;
- breakup of groups;
- formation of groups.

All of the listed properties of the TF, except stationarity, are taken into account when calculating the PC. The stationarity property of a TF is the existence of a period of time when the traffic intensity of a TF can be considered constant. Analysis of statistical data on changes in the intensity of traffic of the TF, obtained from the results of the functioning of the automated control system shows that the period of stationarity of the TF changes throughout the day and depends on the state of the TF (Petrov, 2020).

To achieve this goal, it is necessary to solve the following tasks:

- analyzing the daily change in traffic intensity on urban highways;
- setting the range of changes in the intensity of TF per day;
- determining the minimum and maximum period of stationary TF;
- predicting the dependence of the period of stationarity on the intensity of TF.

As a result of solving the set tasks, it will be possible to improve the following performance indicators of the automated control system:

- reducing the number of stops in the area where the automated control system operates;
- reducing vehicle delays;
- reducing the likelihood of congestion;
- reducing the length of the next vehicle.

The main task is to form a hypothesis of the dependence of the period of action of the PC on the intensity of the TF movement based on the analysis. The object of the study is the movement of TF along the urban road network of the city.

Materials and methods

The choice of the traffic flow control mode (road traffic) must be carried out in accordance with the values of the TF characteristics – intensity, speed, density. The main controlled characteristic is the intensity of TF, which varies throughout the day, week and year (Braylovsky and Granovsky, 1975). As an example, we consider changes in the intensity of traffic flow obtained on Voronezh Moskovsky Avenue (ATCS introduced in 2018) (3 lanes in each direction, average roadway width 25.3 m), which is shown in Figure 1.

The analysis of the graphs shows a constant change in the intensity of TF and the transition from one state to another, which implies the need for timely change of traffic control modes. Changes in the intensity of TF movement lead to changes in such properties as stationarity and stochasticity. In the free state of TF ($\lambda < 350$ aut./h), stationarity and stochasticity have little effect on the change of control modes. With a connected TF ($\lambda > 650$ aut./h), these properties must be taken into account when choosing the moment of changing the control modes and the period of its operation. The period of operation of this mode can range from 30 minutes (with two-phase regulation) to 2 hours.

The main control actions within the framework of a single regulatory regime (coordination program – PC) of the ATCS are:

- cycle duration for PC;
- the duration of the phases in the cycle;
- the magnitude of the phase shift;
- the validity period of the PC;
- time to turn on the PC.

The discrepancy between the listed control actions of the current transport situation leads to the formation of congestion for 30-60 minutes. This is often observed in the associated state of TF. Currently, on urban highways, the associated state of TF is observed from 9:00 to 19:00 hours.

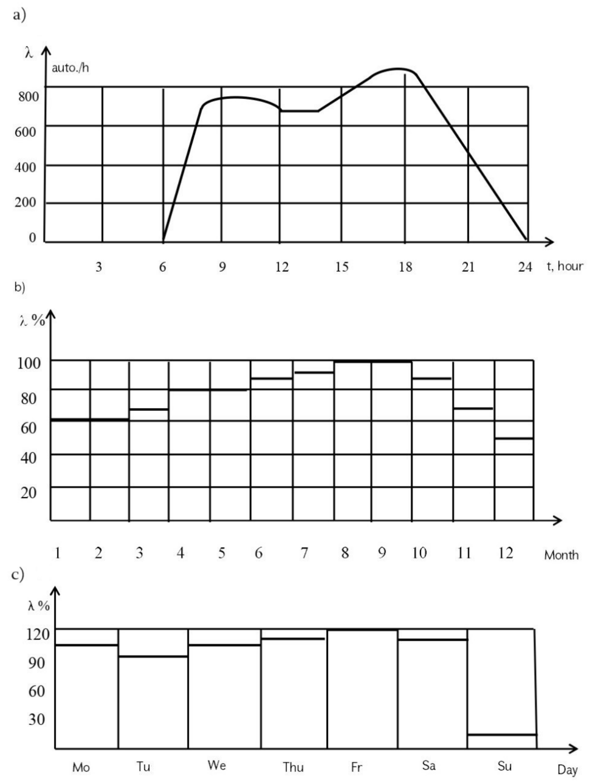

Figure 1. Change in traffic intensity of the TF 2022 a) during the day b) during the year c) during the week *(composed by the authors)*.

To solve the assigned tasks, the following actions must be performed:

- considering the procedure for changing modes;
- formulating requirements for measuring the intensity of TF traffic;
- considering the algorithm for changing the PC;
- formulating requirements for calculating the validity period of the PC.

The main modes of traffic regulation by means of ATCS are:

- single-program coordinated management;
- multi-program coordinated management;
- adaptive coordinated management;
- dispatch control.

The most common traffic regulation regime of the ATCS is strict multi-program coordinated management. To implement this mode, you need a PC library and a PC changeover map. The PC library is calculated in advance based on statistics on changes in traffic intensity on urban highways. Data on changes in the intensity of TF movement can be obtained in advance using a combination of the following measurement methods:

- full-scale method,
- transport detectors (systems and portables),
- video cameras.

The road video surveillance system is an integrated platform designed for operational monitoring and management of the road situation. It carries out continuous monitoring of the state of road infrastructure, collects data on traffic flow and emergency situations, as well as promptly alerts dispatchers about incidents. The functionality of this system is implemented using advanced video analytics technologies, which allow to automatically process video data and identify various anomalies and situations on the roads (Agureev and Atlas, 2012).

The main advantage of rigid multi-program coordinated control is the ability to obtain data for calculating modes in advance. During the operation of the automated control system, the error in measuring data on the traffic intensity of the TF should not exceed 5 %. Otherwise, an error will occur when selecting the mode (PC) and, as a consequence, the following problems will arise in the group and connected state of the TF:

- incorrect distribution of the green signal in the cycle and, as a consequence, disproportion of TF queues in different phases;
- violation of the "Green Wave";
- occurrence of congestion.

The following factors influence the operating error of vehicle detectors:

- the presence of snow (closes the marking);
- TF intensity;
- light level;
- increased humidity.

These factors affect the measurement error up to 100%.

Mathematical modeling of traffic flows is becoming an integral part of the development of automated traffic control systems (ATCS). The study of the dynamics of both individual vehicles and flows in general at various levels - from micro to macro - using a variety of physical and mathematical models, provides forecasting of the overall situation on the roads and the development of effective algorithms to minimize traffic delays (Agureev, et al., 2013). These studies are inextricably linked with the availability of modern technological solutions and software, which provides a wide range of opportunities for testing and approbation of various automated transport infrastructure management systems. Thus, the adaptation of mathematical models to a modern technological base is an important step for the successful implementation of traffic management systems (Gasnikov, 2013).

Results and discussions

Thus, in order to ensure the high-quality operation of the automated control system in the strict multi-program control mode, the following conditions must be met:

- statistics on changes in traffic intensity should be collected in advance;

- measurements should be repeated with a range of readings of no more than 5 %.

Based on the system analysis of the work and the results of the previous section, the following statements can be made:

- during the day, the TF goes from a free state to a group state: connected and back;

- in the free state of the TF, the traffic intensity of the TF increases rapidly since the combination of intensities in all phases of the intersection is significantly less than the value of the saturated flow:

$$\sum_{i=1}^{n} \lambda_i << S, \tag{1.1}$$

where, λ_i- the intensity of TF in the i-th phase, n - number of phases, S - the value of the saturation flow.

- in the bound state of TF, the intensity of TF changes very slowly since the totality of intensities in all phases of the intersection is close to the value of the saturation flow:

$$\sum_{i=1}^{n} \lambda_i \to S. \tag{1.2}$$

The analysis of the graph of changes in vehicle traffic intensity in Fig. 1 (a) confirms the conclusions drawn.

Thus, summarizing the conclusions drawn, the following hypothesis can be formulated:

- the period of operation of each mode (PC) should increase with increasing traffic intensity;

- to solve the problem, it is proposed to use the following equation:

$$y = ax + b, \tag{1.3}$$

where, y is the validity period of the PC, x is the traffic intensity of the TF, a and b are constant coefficients.

Currently, with traffic light regulation of the entire road network of the city of Yerevan, traffic at intersections is working under strict traffic light regulation (in peak time mode), as a result of which during off-peak hours (10:15-12:00, 15:00-16:30 and 21:00-8:00) there are major delays caused by an excess of green signals on secondary routes. During rush hours (8:30 - 10:00, 13:00 - 14:30 and 17:00 - 19:00) almost 70-75% of the road network (9 points on the 10-point scale of the Yandex map) directions are considered dense, overloaded situations caused by high traffic volumes (Sargsyan and Khachatryan, 2023).

Experimental studies conducted on Mashtots Ave. (3 lanes in each direction, average roadway width 24.8 m) in Yerevan from September 10 to 20, 2023, made it possible to obtain statistical data on the intensity of TF and the time period of their preservation (Fig. 2), which will be changed after the introduction of the ATCS, and will change the period of activity of the given project, depending on the stationarity of the TF.

After processing the data using the least squares method, the regression equation and the values of the coefficients a and b in the formula 1.3 were obtained.

$$t = 0.1\lambda - 5, \tag{1.4}$$

where, t– the validity period of the PC, λ – intensity of the TF.

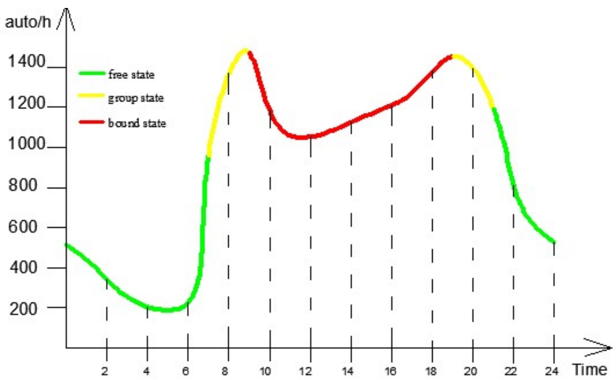

Figure 2. TC condition and average traffic intensity *(composed by the authors)*.

Conclusion

Thus, the following conclusions can be drawn:

A review of the methods of traffic control by means of automated control systems has been performed. It is established that the most frequently used mode is rigid multi-program management, which consists of a library of coordination programs. The task of the study is set up.

Based on the system analysis, the dependence of the period of operation of each PC (the period of stationarity) on the state and intensity of TF has been established. It was found out that with an increase in the intensity of TF movement, the stationary period increases from 30 minutes to 2 hours.

A mathematical dependence of the control parameter affecting the efficiency of TF control intensity is proposed.

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Declarations of interest

The authors declare no conflict of interest concerning the research, authorship, and/or publication of this article.

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