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SIMULATION OF THE ADVANCE TIME OF PERMISSIVE TRAFFIC SIGNAL ACTIVATION FOLLOWING THE COORDINATION PLAN ON ARTERIALS: PLAN OF THE EXPERIMENT

Summary. The paper presents a methodology for evaluating the accuracy of analytical models for determining the advance time of a traffic light at the next intersection in coordination. The presented analytical models are based on the assumptions of a constant average and linearly decreasing acceleration of vehicles when moving from the stop line of the intersection. As a tool for comparing analytical models with the real characteristics of the transport process, it is proposed to use the traffic micromodeling tool – PTV VISSIM. The developed plan of the simulation experiment is to determine the advance time of the traffic signal in coordination and consider the specific conditions of the transport process for the

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selected object of study. It is the basis for obtaining the starting values of the advance time.

Keywords: advance time, coordination plan, progression, traffic management

1. INTRODUCTION

Efficient traffic management (TM) in cities is a subject of constant attention from state authorities, local governments, and specialists (experts). The key and most numerous elements of urban TM systems are single-level street intersections, which concentrate on the main traffic management problems, as they cannot provide opportunities for simultaneous movement of all competing traffic and pedestrian flows [1]. Traffic lights are the primary means of traffic control at the busiest street intersections. Suppose the traffic lights are located close to each other. In that case, it is an effective practice to introduce the coordinated operation of such traffic lights to organize the most unhindered movement of vehicles in one or more directions of traffic – the progression.

It should be noted that the existing coordination methods must consider the transport process peculiarities when road users move along arterial roads thoroughly. Such features include group arrival of vehicles to the next intersection in the coordination plan (CP), interaction of the main traffic flow (TF) with vehicles of minor directions that become obstacles, harmonization of vehicle speed on coordinated arterial sections, etc. Considering these features will allow the specialists in TM to create new approaches to CP formation, which can lead to the uniform movement of all participants in the transport process on coordinated arterial sections.

The advance time of the green traffic signal is one of the most critical parameters affecting the efficiency of coordinated traffic signal control. It ensures the continuous movement of the progression platoon on coordinated sections of the road network (RN). The advance time is the time that allows the first vehicle in the queue to move at the selected promotion speed to reach the last vehicle in the queue when the latter reaches the promotion speed. The position of the last vehicle in the queue at the next intersection may be different, and it determines the time from the green traffic signal to the moment when this vehicle reaches the intersection speed. Therefore, the advance time required to ensure unhindered progress depends mainly on the number of additional vehicles in each lane of the coordinated arterial.

The high relevance of the task of finding the optimal values of the advance time in the operation of coordinated traffic signal systems at the arterials is that it is taken into account in:

- the traffic light cycle length. This time is added to the primary traffic light cycle, forming the actual cycle length. This is necessary for the additional vehicle to accelerate to the progression platoon speed behind the traffic signal (TS). Including the advance time in the cycle will reduce the capacity of the coordinated intersection, as it will be free of vehicles for most of the advance time. However, conventional methods for calculating cycle length do not consider advance time based on a constant saturation flow. This indicates the practicality of considering other methods of determining the cycle length than those based on the generally accepted Webster's formula;
- the offset time of the beginning of the traffic light cycle. The offset time is the interval between the moment when the permissive signal for the progression platoon is switched on at the current and previous intersections in coordination. And since the start of the cycle in coordination is usually the beginning of the primary cycle assigned to the progression, it also determines the difference between the cycle start times at these intersections. This offset is essential for optimizing the operation of traffic signal systems, affecting the smoothness of

traffic flow, reducing congestion, and improving the distribution of traffic at intersections and arterial sections.

The primary goal of the study is to evaluate the accuracy of previously developed analytical models that allow for establishing the advance time value for turning on the green traffic signal at the next intersection in the CP.

Since such an evaluation requires the creation of rather specific conditions for conducting the experiment, which is extremely rare in the actual transport process, it is necessary to use microsimulation of traffic flow on a coordinated arterial section to achieve the goal. The tool for developing the simulation model is the specialized software product PTV VISSIM, which has all the necessary capabilities to obtain reliable results for modeling the selected object of experimental research.

2. MATERIALS

2.1. Introducing the analytical models to be evaluated

In this study, we evaluate two analytical models for determining the advance time for switching on the permissive traffic signal in a CP based on the following:

- the average acceleration of the first vehicle in the progression platoon from the stop line of the first intersection in the CP [2];
- the linearly decreasing nature of the change in vehicle acceleration when the vehicle moves from a stop line [3].

According to [2], the advance time at the next coordinated intersection at constant acceleration is calculated according to the following dependence:

$$\Delta t_d = \frac{V}{2a} + \frac{L}{V} + T_s \, , \tag{1}$$

where V is the speed of the progression platoon, [m/s]; a is the average acceleration of the first vehicle in the platoon, [m/s^2]; L is the average length of the additional vehicle, [m]; T_s is the safety interval, i.e., the time interval required to cover the safety distance at the current speed, [s].

The model of linearly decreasing acceleration is an attempt to describe the acceleration patterns of vehicles more adequately than constant acceleration. According to the research of G. Long [3], for drivers with a moderate driving style, it looks like this:

$$a(t) = A + b \cdot v(t) \, , \tag{2}$$

where $a(t)$ is the speed of the vehicle at time t, [m/s^2]; A is the maximum acceleration of the vehicle when starting from a stop line, [m/s^2]; $v(t)$ is the speed of the vehicle at a given time t, [m/s]; b is a parameter that takes a negative value and represents the rate of decrease in acceleration with increasing speed, [s^{-1}].

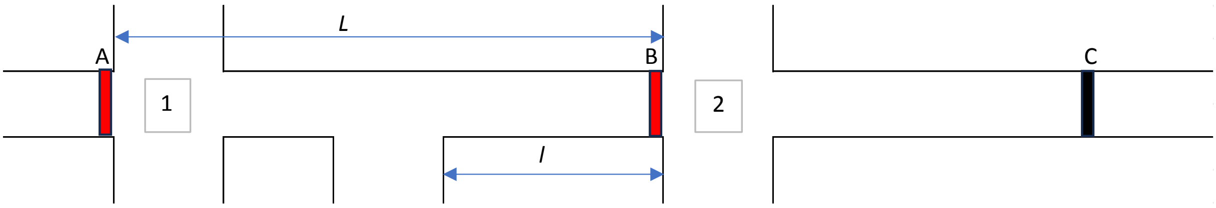
By analogy with dependence (1) and subject to the appropriate mathematical operations, the dependence for determining the advance time, taking into account the linearly decreasing nature of the acceleration, will be as follows:

$$\Delta t_d = \frac{1}{b}\left[\ln\left(\frac{b \cdot V}{A}+1\right)\cdot\left(1+\frac{A}{b \cdot V}\right)-1\right]+\frac{L}{V}+T_s\,. \qquad (3)$$

Taking into account the previously obtained results [2] of estimating the lower limit of the advance time for two developed models for one additional vehicle that impedes the movement of a progression platoon, it was found that the value of the advance time of switching on the green traffic signal at the next coordinated intersection will depend on both the characteristics of the arterial section and the characteristics of the vehicles moving along it. Thus, the first one includes the length of the arterial section between the TS in the CP, the number of traffic lanes on the section, etc., and the second ones include the magnitude and nature of the change in the acceleration of the vehicle when starting from a stop line, speed, etc.

2.2. Description of the object of experimental research

Since this study makes only the first attempt to estimate the advance time on the example of the impact of one additional vehicle on the progression platoon, it is advisable to choose a single-lane section of the arterial with two controlled intersections equipped with traffic lights as the object for the experimental research. This will allow us to analyze in detail the impact of an additional vehicle on the movement of the progression platoon on the coordinated section of the arterial, without the mutual influence of vehicles from the progression platoon that could move along other arterial lanes. The arterial section (before the second intersection) also allows for entering additional vehicles moving in the same direction as the main flow (progression platoon). The scheme of the object of experimental research is shown in Fig. 1.



Symbols:
L is the distance between the stop lines of intersection 1 and 2, m; *l* is the distance between the place where additional vehicles enter the arterial section, and the stop line of intersection 2, m; A and B are, respectively, the locations of the stop lines of intersection 1 and 2; C is the control point for measuring the travel time of progression platoon

Fig. 1. Scheme of the arterial section for the experiment in VISSIM

2.3. Justification of the range of changes in the length of the arterial section between the TSs for the simulation experiment

It should be noted that within this part of the experimental research, even before the actual modeling of vehicle movement, one of the issues that have not been fully resolved is the justification of the range of changes in the length of the arterial section between traffic lights (intersections) 1 and 2 (Fig. 1). In this regard, it is worth noting that researchers on the organization of coordinated traffic signal systems have different opinions on their effective placement relative to each other. For example, [4] notes that there is no universal formal rule for the minimum distance between adjacent intersections in a CP, and the authors of [5] state that the optimal distance between controlled intersections depends on the speed, intensity of traffic flow, and planning characteristics of the intersection.

Basic information on the issue of justifying the distances between the TSs is in the guidelines on TM, as well as scientific reports and articles, the brief results of which are given in Tab. 1.

Tab. 1

Results of the analysis of sources on selection and justification of the length of arterial sections between TSs in the CP

Source	Length between TSs	Comments
Austroads 2019 [6]	Over 1 km	Coordination is beneficial when TSs are installed at consecutive intersections
Bastable [7]	Less than 500 m	At this distance between TSs, the reduction in delays and stopping times is usually greater than 20%
The Metropolitan Planning Organization [7]	2640 ft ≈ 800 m (ideal distance) 1600 m or more (arterial-arterial) 800 m and more (arterial-non-arterial)	When the distance between TSs is less than a quarter mile (1320 ft ≈ 400 m), traffic flow along the arterial may be disrupted
CPPAS [8], NASEM 2014 [10]	At least 800 m	Considered traffic levels on the arterial
CEREMA 2002 [4]	Minimum distance of 250 m	This distance may be acceptable if the section's characteristics allow the progression platoon to move without obstacles
FHWA 2013 [11]	More than 300 m	Smaller distance between TSs does not contribute to the coordination effect
FHWA 2005 [12]	1200 m	When the TSs are placed at this distance, coordination is particularly effective
Roiko Y., Grytsun O. [13], Khitrov I., et al. [14]	Not more than 800 m	At a distance of more than 800 m, the progression platoon breaks up
Kondrashova V.D. [15]	Not more than1000 m	When introducing arterial coordination
NCHRP 1999 [16]	330 m (cycle length is 60-70 s) More than 600 m (cycle length is more than 100 s)	Assuming the speed of a progression platoon is 50 km/h, it is assumed that each additional TS (more than two per mile) leads to a 7% increase in travel time
LRAS [17]	600 m	This distance between TSs ensures almost optimal mobility during peak loads in conditions associated with high TF

Jiawen Wang et al. [18]	The average distance is 189 m	The paper considers optimizing traffic and pedestrian flows at intersections close to each other. An optimization model of delays is built, significantly reducing vehicle and pedestrian delays
Nesheli M.M. et al. [19]	780 m	TRANSYT7F simulation results show that after coordination, delays, travel times, and congestion are reduced

The results of the analysis of regulatory and scientific sources on the issue of determining the effective distance between TSs in a CP indicate that the primary influence on the length of arterial sections in coordination is exerted by intensity, TF speed, and cycle length - this is, to a greater extent, under the formation of a new RN and the functioning of the existing one. This raises the question, "What should be done when the road network is already in place, and is it necessary to solve traffic congestion problems on the genuine arterial?" In this case, it is advisable to use traffic micromodeling tools, which indicate the possibility of obtaining an effect even for objects where the TSs are very close [20-22]. However, it should be noted that the results obtained in these studies need to be thoroughly tested on natural objects.

In addition, it is also worth noting that there is a significant difference in the evaluation of the limit values of the range of changes in the length of arterial sections in the CP by Ukrainian (300-400 m) and foreign (600 m Europe (with exceptions), 800-1200 m USA, Australia) researchers. The main reason is the existing planning characteristics of RN elements and city transport planning approaches.

Considering the above information, analyzing examples of CP implementation in Ukrainian cities would be advisable to obtain more precise limits of the range of changes in distances between the TSs.

Turning our attention to the sections of the Ukrainian cities' arterials where coordination has been implemented, or attempts have been made to implement it, it should be noted that the distances between regulated intersections in the CP differ significantly from those indicated in the above foreign sources. For example, in Rivne, on the section along Myru Avenue, the average length of the section between the traffic signals in the CP is about 245 m; in Kharkiv, on Nauky Avenue, 348 m; in Dnipro, on Naberezhna Peremohy Street, 421 m; in Chernihiv, on Heroiv Chornobylia Street, 372 m; in Vinnytsia, on three main streets: Kyivska (9 TSs), Bratslavska (5 TSs) and Nemyrovske Highway (8 TSs) – 456 m.

To obtain more precise guidelines for the limits of the range of possible distances between the TSs of already implemented CPs in Ukrainian cities, we will conduct a statistical analysis of the above information on the lengths of arterial sections between TSs in CPs, which was expanded by using data obtained from the Kharkiv-Signal utility company, whose specialists solve the issues of traffic regulation in Kharkiv city.

The input information processing provided a data set consisting of 66 values of the lengths of the sections between the TSs. After statistical processing in STATISTICA 10, the variation series' main characteristics were determined and presented in Tab. 2.

The obtained results do not provide an unambiguous answer about the limit values of the range of changes in the lengths of sections between the TS in the CP, which can be used for the simulation experiment. However, taking into account the authors' practical experience in the development of CP, as well as the results of the analysis of scientific and practical works, which present data on the selection and justification of the length of sections between controlled intersections, it can be noted that the upper limit of the search range can be selected at 800 m, as the one at which the progression platoon is likely to scatter. As for the search for the lower limit of the range, it is necessary to note the practicality of using such a characteristic of the variation series as the mode. Unlike static (simple) averages, which are essentially an abstract characteristic of a set, mode is a specific value that coincides with certain variants of the set components and reflects the fundamental nature of a random variable.

The results of the statistical analysis of the variation series do not give an unambiguous answer regarding the specific mode value in the data sample, so it is advisable to determine it by the distribution of the lengths of the sections between the TSs on the arterial. In this case, at the first stage, it is advisable to determine the required number of intervals for which the well-known Sturges formula is used [23]. With a sample size of 66 units, we obtain a value of the number of intervals equal to 8. For this number of intervals of the available variation series, the distribution of the lengths of the sections between the TSs on the arterial was constructed using STATISTICA 10 (Fig. 2).

Tab. 2

Characteristics of the variation series of values of the lengths of sections between the TSs on the arterial

Sample characteristics	Values
Sample size, [units]	66
The minimum value of the distance between the TSs, [m]	153
The maximum value of the distance between the TSs, [m]	1055
The average value of the distance between the TSs, [m]	459.3
Standard deviation, [m]	210.4
Mode, [m]	several with a frequency of 2 290; 286; 431; 530
Median, [m]	409.5

To determine the value of the mode, we will use formula (4) and simultaneously make a graphical visualization of the calculation of this indicator (Fig. 2).

$$Mo = \frac{f_{mo} - f_{mo-1}}{(f_{mo} - f_{mo-1}) + (f_{mo} - f_{mo+1})} \cdot i_{mo} + x_{mo} \tag{4}$$

where x_{mo} is the lower boundary of the modal interval, [m]; i_{mo} is the width of the modal interval, [m]; f_{mo} is the frequency of the modal interval, [units]; f_{mo-1}, f_{mo+1} is the frequency of the previous and next interval relative to the modal interval, [units].

$$Mo = \frac{19-6}{(19-6)+(19-14)} \cdot 125 + 225 = 315.3 \text{ m}$$

The obtained mode value may correspond to the lower boundary of the range of changes in the lengths of sections between the TSs on the arterial, which will be used for the simulation experiment in VISSIM.

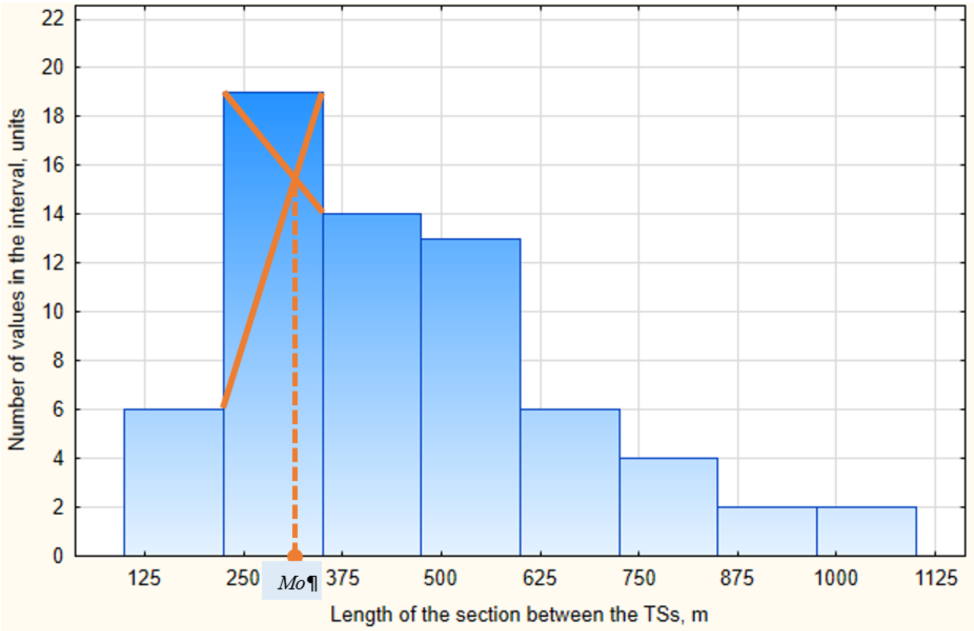


Fig. 2. Distribution of the values of the lengths of the sections between TSs on the arterial by intervals

Based on the above information, it is quite possible to state that for experimental studies of models for calculating the advance time of the permissive signal inclusion at the next controlled intersection in the PC, it is advisable to use the range of changes in the length of the sections between two adjacent TSs within 300-800 m with a change step of 100 m. It should be noted that the lower limit of this range corresponds to the current situation with the location of TSs on the arterial sections of Ukrainian cities where coordination has been implemented, and the upper limit of 800 m is taken as the one beyond which a platoon in the CP is likely to scatter.

2.4. Description of the sequence of vehicle movement modeling on the selected object

Finding the optimal advance time values is a relatively specific task, characterized by the influence of many random factors: the nature of the vehicle acceleration, vehicle speed, driver behavior and reaction, traffic situation, etc. Besides, there is a need for practical and thorough methods for its determination and consideration when determining the cycle length in the CP. Currently, the leading practice for verifying and testing the results of CP implementation is micro-simulation tools, which, unfortunately, do not have appropriate tools for directly determining the advance time, including VISSIM software. Therefore, to determine the advance time, it is necessary to create specific conditions for vehicle movement on the arterial section in VISSIM, which will be described below.

The general process of model formation in VISSIM consists of the following steps:

- RN segments modeling;
- TS placement and modeling;
- modeling of incoming flows (intensity, composition of vehicles, and flow distribution by directions are set);
- modeling of vehicle routes;
- modeling of conflict zones with an indication of priority rules;
- simulation of vehicle movement itself.

Simulating the movement of vehicles in the model implies that the progression platoon starts from the stop line of intersection 1 and drives to control point B at intersection 2, where one additional vehicle is waiting for them each time.

The control point C is located so far from B that, with the maximum advance time and any length of the A-B section, the vehicle starting from the stop line of the 1st intersection does not overtake the additional vehicle, and the additional vehicle passes point C, at its maximum (cruising) speed. The distance traveled by the additional vehicle from the stop line of intersection 2 to point C does not depend on the length of section A-B. The length of sections B-C will depend on the power characteristics of the additional vehicle, the driver's behavior, and the advance time value for the traffic signal at intersection 2. The interest in knowing the length of sections B-C from the point of view of the simulation experiment is that it is possible to track the merging point of the progression platoon and the additional vehicle at different advance time values in each series of experiments.

An additional vehicle can appear on the arterial by creating a minor road in VISSIM 100 m from intersection 2. The distance is optional in this case; the main thing is that by the time the vehicles from the progression platoon approached the second intersection, the additional vehicle was in a static position in front of the stop line of the second intersection. The appearance of additional vehicles on the arterial and their number are regulated by the TS, which is set when the additional vehicle leaves the minor road.

The parameters that vary in the simulation model are the length of the section between TSs A-B (it varies from 300 m to 800 m in increments of 100 m), the advance time of the permissive signal activation at intersection 2 (it varies from 0 s to 10 s), and the Random seed increment (a VISSIM setting that affects the formation of the composition and interval of the traffic flow in the simulation model).

The sequence of simulating vehicle movement in the developed model is as follows:

(1) At the first stage, the basic settings of the model are carried out: the parameters of the TS operation (the length of cycle, its intermediate and primary cycles) at intersections 1 and 2, as well as on the minor road for allowing the additional vehicles enter the arterial are determined; the parameters of the vehicles moving along the coordinated section of the arterial and the minor road are selected; the vehicle movement model (driving style) is determined, which ensures uniform movement of the progression platoon when they reach their cruising speed in the simulation (in this experiment, the Wiedemann 99 model is used). The secondary direction is configured so that only one additional vehicle is allowed to pass the traffic lights. The speed limits respond to the conditions of vehicle movement in urban areas.

(2) In the second stage, the progression platoon movement is modeled under the conditions of its free movement (unhindered movement of the progression platoon through the section between intersections 1 and 2 after starting from the stop line of intersection 1). The obtained value of the movement time through the A-B section is used to set the TS at intersection 1 as the advance time of the traffic signal activation at Intersection 1. The vehicle's maximum speed through the section and its acceleration when starting from the stop line of intersection 1 are also recorded.

(3) At the third stage, the simulation of the movement of the progression platoon through the coordinated section of the arterial, which meets an additional vehicle near the stop line of intersection 2, is carried out when different advance time values of the traffic signal activation at intersection 2 are set. At the same time, the travel time of the progression platoon through sections A-B and A-C is recorded. In each series of experiments, one value of the advance time is chosen that corresponds to the minimum value of the time for

overcoming section A-B by vehicles from the progression platoon, that is, under conditions of unhindered movement through the section (when coordinated cars do not slow down on the approach to intersection 2).

3. DISCUSSION

The following factors should be considered when searching for the optimal value of the advance time: length of the section between traffic lights. The longer the section is, the longer the advance time should be, as well as vehicle speed (power characteristics of vehicles). The higher the speed of vehicles is, the shorter the vehicle's time should be and the intensity of the traffic. If the traffic intensity is high, the vehicle's time should also be longer to ensure all vehicles in the progression platoon can pass through the first TS before closing.

Regarding the lengths between the TSs in the CP, it is crucial to consider the advance parameter, as it has a critical impact on increasing the cycle length of the traffic lights. This is because the vehicles at the first TS need enough time to pass through the section before the red signal at the second TS turns on. If the advance time is insufficient, the first vehicles in the progression platoon may hit an additional vehicle or get stuck at a red signal at the second TS, resulting in delays.

4. CONCLUSIONS

The advance time of the TS's previous activation is an essential parameter for setting up effective TS management in coordinated arterial sections. Its use allows for unhindered movement of the progression platoon. The current TM guidelines do not contain information on the selection and justification of the advance time value, but only provide some recommendations for determining the offset value of the traffic signal activation at the next intersection in the CP without specifying the advance time.

Finding the advance time is quite specific. Its solution requires creating special conditions for the movement of vehicles on the object selected for the study, which is almost impossible to reproduce and provide on an actual section of the road network. Therefore, it is advisable to use traffic micro modeling tools, such as VISSIM, as the primary tool for modeling the advanced time.

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