

**Keywords:** traffic signalization; crossing; traffic delays; energy efficiency

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## **IMPROVING THE EFFICIENCY OF VEHICLE OPERATION AND ITS ENVIRONMENTAL FRIENDLINESS WITHIN THE CONTROLLED CROSSINGS**

**Summary.** This paper is devoted to improving both the efficiency and the environmental friendliness of road vehicles during their operations through optimization of traffic phase duration within the controlled crossings. A novel criterion to optimize traffic phase duration within a controlled crossing is proposed. The proposed criterion supposes the minimal total delays of all road users waiting for a permissive traffic signal at the crossing and takes into consideration both pedestrian density and the number of passengers in vehicles. The calculation technique for the traffic phase was proposed, according to which delays of all road users were optimized, helping to improve the efficiency of vehicle operation within crossings. Based on the method, a technique to control traffic within crossings is developed and tested. Comparative analysis confirmed the decrease in unproductive delays of vehicles within the controlled crossings by contrast with the traditional approach. The technique makes it possible to reduce the delay of road users by 15-20% depending upon road crowding, the number of pedestrians, and passengers. Owing to the decreased period of waiting for a permissive traffic signal, the energy efficiency of public transport increases.

### **1. INTRODUCTION**

According to data reported by the World Health Organization (WHO) [1], pedestrians are 26% of all the victims of the road traffic accidents happening in European countries. According to WHO, pedestrian–vehicle collision avoidance is the key strategy to improve accident records. Traffic signalization is one such measure. At the same time, this control results in increased traffic delays in front of crossings for all road users. Such traffic delays factor into more energy consumption by electric transport and more fuel consumption by motor vehicles, leading to degradation of the city’s environment.

The Webster method is the most popular to calculate control modes [2]. When in use, the duration of the basic phase periods is identified according to their phase coefficients. The phase coefficient is characterized by the vehicle density–saturation flow ratio. However, the difference between the processes when vehicles are starting and pedestrians are stepping to a crossing cannot help determine the density flow of pedestrians for traffic signalization. In this case, the Webster method is applied to solve a system of equations [2], making it possible to determine the duration of a controlling cycle taking into consideration both the traffic density and the minimum period to let pedestrians pass irrespective of their motion density.

Such an approach involves identifying the equivalent setting of the pedestrian phase duration of a phase coefficient. In this context, the proportional ratio between phase coefficients and durations of basic periods of corresponding phases, determined according to the Webster method, remains invariant. The main limitation of the approach is as follows: in practice, the calculations substitute pedestrian flow for reduced phantom traffic involving a certain period being equal to the pedestrian phase. Thus, pedestrian density cannot have an effect on a traffic light cycle duration.

Moreover, minimization of the reduced transport unit delay does not involve delay for passengers. The transition from physical traffic flow to a reduced one occurs through the reduction coefficients taking into consideration the dynamic characteristics of the vehicles [3] rather than their passenger capacity.

The average number of passengers, in a vehicle, depends upon the passenger capacity of the vehicle as well as its efficiency. It is known that the occupancy rate of public transport is much higher than that of a private car. For instance, [3] recommends specifying the efficiency of passenger capacity for a bus and a car as 0.75 and 0.24, respectively.

Paper [3] proposes the following formula to determine the cycle duration in the context of a controlled crossing:

$$T_c = \frac{1,5(T_v + t_{OT}^p) + 5}{1 - y}, \quad (1)$$

where  $T_v$  is the time lost during the controlling cycle (i.e. overall duration of transient intervals), s;

$t_{OT}^p$  is the duration of the primary cycle in the pedestrian phase, s; and

$y$  is a phase coefficient of the traffic phase of control.

In this context, the basic period of a traffic phase is determined according to [3] the following formula:

$$t_{OT}^t = T_c - T_v - t_{OT}^p. \quad (2)$$

It stipulates the necessity to separate the minimum required time for pedestrians to cross a roadway; the remaining share of the cycle is for traffic not involving the transient interval. In practice, the restriction of the maximum duration of the controlling cycle is the only limitation of the approach.

## 2. ANALYSIS OF RECENT RESEARCH

Improvement of traffic signalization efficiency at intersections is among the most urgent global problems. Most of all, a mode of traffic signalization is considered from the viewpoint of pedestrian safety and traffic delays.

Research in [4] confirms the importance of considering the duration of pedestrian delay in front of a crossing while determining traffic signalization parameters. Minimization of pedestrian delay and maximization of the total capacity of a crossing are proposed as the basic criteria to optimize the duration of a permissive traffic signal. Paper [5] demonstrates a stochastic model on the basis of a mass service theory. The theory helps determine delays of traffic and pedestrians in front of a controlled crossing. Minimization of controlling cycle duration has been considered a criterion while optimizing the traffic-light mode of a crossing. In this context, the minimum duration of an enabling signal is defined within the output data.

The study [6] confirms the positive effect of traffic-light control within crossings on traffic safety. The effect is especially notable for elderly and handicapped individuals. However, disregard of controlling signals by pedestrians is the main risk for traffic participants. The number of pedestrians, waiting for the enabling signal, and traffic intensity are the basic factors leading to such violations of traffic safety rules. Paper [7] considers the maximum queue time before a signal and the transition interval of the traffic phase as the key factors correlating positively with the number of violations of controlling signals by pedestrians.

A study [8] highlights that the majority of current methods aimed at the determination of the duration of an enabling signal for vehicles within crossings ignore pedestrian delays. It is considered that they are compensated for at the expense of decreased vehicle delay. However, for cities where pedestrian traffic is high, this idea is not feasible. A model, minimizing weighed delays of vehicles and pedestrians, has been proposed. A method of determining queues has been applied to identify delays of vehicles and pedestrians. An empirical model has been used to identify pedestrian traffic delays. Overall optimization helped reduced the average delay of a person by 10%, with no changes in the controlling cycle duration. If the cycle varies then time saving is 44%. The study [9] aimed to optimize delays of vehicles and pedestrians within the controlled crossings with a two-stage pedestrian passage. The modeling is performed according to the quadratic programming method determining both the optimum mode and the possibility to allow pedestrians to pass synchronously from different sides of their refuge island. Moreover, a number of studies have focused on the problems of efficient functioning of controlled crossings. Paper [10] reports that delays in front of traffic lights play an important role in overall delays of public transportation vehicles within cities. The delays are negative for traffic accuracy and its optimum speed. Furthermore, they result in the prolonged operation of vehicle engines in the modes of acceleration and idle run, having a negative effect on the energy efficiency of the vehicles. Increased energy consumption to move a kilometer limits the possibility to replace buses by electric buses, preventing ecological upgrading of public transport. The approach, described by the study, of controlling mode determination to assign priority to buses, takes into account both the vehicle type and the number of passengers in the vehicle. The algorithm to determine parameters of a traffic light mode, considered by the paper [11], is based on the Webster method. This confirms the expediency of the practical use of the classical approach if it is modified.

Numerical results of studying how pedestrians cross a traffic flow through the signalized crosswalks or their vicinities show that the vehicle-pedestrian ratio is curvilinear as to the delay period of a pedestrian incoming cycle; careful pedestrians needlessly spend more time to pass through a road than violent ones. The pedestrians, stepping across a street in the neighborhood of a signal light, influence heavily both their stoppages and those ones by transport facilities. If pedestrians may walk across the road using the space between unhurried transport facilities, their stoppage hardly prolongs [12, 13].

Taking into consideration the running traffic features on highways and active roads at a traffic-controlled intersection, the control of arrival of a transport vehicle and the characteristics of the vehicle passing through the parking line are illustrated; then, a queuing model of parking delay is identified. The ratio of the length of a single parking line and the geometric nature of the traffic-controlled intersection as well as the traffic plying on the road between traffic lights have also been studied. Moreover, a phase-lag model has been determined. Thus, the lag model, matching any flow intensity, has been introduced to correct the established model and yield more useful outcomes.

Two variants of stoppage changeability have generally been applied for traffic-controlled intersections: arriving time-controlled stoppage changeability for certain transport vehicles and standard controlling stoppage changeability. The former brings into focus stoppage by certain vehicles; the latter is linked to the average outcome of traffic signalization for the whole traffic flow for the duration of the estimation period. In the context of several methods of estimation, not many studies have been carried out to facilitate a broad-based evaluation of the scales of changeability. The problem [14] is solved by comparing the two variants of stoppage changeability within individual, constantly monitored traffic junctures based on two analytical models taking into consideration both the probabilistic nature of the approaching vehicle and a traffic jam. The outcomes demonstrate that under unsaturated conditions, stoppage of some vehicles is apt to lead to extended distribution and greater variability in contrast with standard controlling stoppage. Under supersaturated conditions, the distribution of both stoppage structures continues with greater variabilities. Various incoming procedures have been found to strongly influence the conjugated stoppage distributions. Moreover, the stoppage distribution size, based on the percentile ranks, is used to evaluate the stoppage uncertainty in terms of various degrees of saturation. In contrast to the standard controlling stoppage, some vehicle delays have been found to have a larger uncertainty level under the unimpregnated conditions; nevertheless, it becomes comparatively specific under supersaturated conditions. All the analyses have certain implications for improved knowledge of stochastic input-output procedures within the operating areas of traffic lights.

Pedestrian–motor vehicle interference in traffic-controlled intersections results in traffic jams as well as slow traffic. In addition, it causes many road accidents. This paper applies a microscopic discrete traffic flow model to analyze the shared interference pedestrian–motor vehicle system within a traffic-controlled intersection. The model relies on the refined NaSch model; traffic lights have been used to notice a driver about the signal light switching. As opposed to the multistage lattice gas model, the pedestrian flow model takes into account the fact that the pace of walking increases steadily when green lights are on for pedestrians to pass. Both models mirror factual aspects of vehicular movement (pedestrian traffic) in everyday life. If the traffic signal lights, then staying of vehicles (pedestrians) in the conflict area results in the stoppage of pedestrians (vehicles). It is assumed that it is impossible for vehicles and pedestrians to synchronize within the conflict area. During simulations, the periodic boundary condition is used for the road and the open boundary condition is used for the crossover. The arrival density of pedestrian flow is assumed in this way to match the Poisson distribution. The fundamental diagram of road traffic flow as well as the waiting period of pedestrians has been computed, and the phase plot, demonstrating the worldwide scale of the model, has also been developed. The measurable parameters of the vehicle (pedestrian) stoppage period, resulting from the pedestrian (vehicle) stay period within the conflict area, are also represented. The simulation shows that there is a significant crack. If the crack is less than the critical value, then the three types of traffic stages (i.e. free flow stage; consistent flow stage; and jamming flow stage) become visible in terms of an increase in density. If the crack exceeds the critical value, then four types of traffic stages (i.e. free flow stage; simultaneous stage; consistent flow stage; and jamming flow stage) are available. The stoppage, resulting from the pedestrian-motor vehicle interaction, depends heavily on the traffic flow state as well as the pedestrian flow state [15].

Paper [16] estimates prediction models of pedestrian accidents and the intensity of vehicle interaction in terms of traffic-controlled intersections in Connecticut involving simultaneous pedestrian phasing or an exclusive one. If simultaneous phasing is present, then pedestrians cross the road along with motor vehicle traffic, moving when the green light is on. If exclusive phasing is present, then, pedestrians cross the road when the green light is on, and vehicles stop when the red light is on. Within each crosswalk, the pedestrians, who crossed it, were recorded and systematized according to the accident severity. The traffic junctures were selected to demonstrate both types of light phasing and control of other physical specifications. In the context of curvilinear mixed models of accident severity, the pedestrians, crossing when their green signal is on, had lower severity of collision in contrast with those who crossed on the green light with simultaneous phasing; however, the pedestrians, who stepped across a street on a green light during an exclusive stage, suffered more heavily. Traffic junctures with simultaneous phasing have fewer pedestrian accidents than those with exclusive phasing, but more dangerous accidents. It is recommended to use the exclusive crosswalk if only pedestrians obey.

To determine the pedestrian regulation phase accurately, one should compute the numerical characteristics of the distribution of pedestrian velocity along the pedestrian crossing. The Urban Street Segment Chapter of the Highway Capacity Manual (HCM) includes methods to evaluate the level of service of urban street segments for drivers. The methods do not include pedestrian activity within zebra crosswalks of urban street segments. Pedestrian activity at unsignaled intersections within the urban street segments results in complicated conditions for vehicles and pedestrians. Thus, the average time for automobiles to pass through this segment increases. There is an inverse relationship between the stoppage of the involved vehicles and the speed at which pedestrians walk. Hence, it is important to analyze the speed at which pedestrians walk within unsignaled intersections. In many studies, the speed of pedestrians has been measured depending according to their age groups; two unsignaled urban intersections were studied. The first objective of this paper is to analyze statistically the determined free-flow pedestrian velocities. The second objective is to show how the results of the study can be incorporated into the Urban Street Segment Analysis Chapter of the HCM. Velocities of 2937 pedestrians were documented and studied. The results showed that the average velocity of teenagers is 1.45 m/s; the average velocity of young adults is 1.55 m/s; the average velocity of middle-age pedestrians is 1.45 m/s; the average velocity of elderly pedestrians is 1.09 m/s; and the average velocity of older pedestrians and senior or disabled individuals is 1.04 m/s [17].



Determination of the optimum position as well as the optimum timing schedule for sections between traffic lights within an arterial section is among the major operational problems since traffic lights are increasingly being set up in densely populated areas of such developing countries as China. Paper [18] presents a multicriteria optimization model as well as an effective algorithm for one- or two-stage of pedestrians within an arterial highway. The model should help identify the optimum position and adequate signal arrangement to equalize the ratio of pedestrian stoppages and highway capability. The model has three distinctive features: (i) the cost for pedestrians and vehicles is considered in terms of the integrated framework; (ii) the location and signal arrangement of the midblock pedestrian crossing are improved in steps; and (iii) a multicriteria optimization procedure has been developed to analyze the efficiency of the midblock pedestrian from the viewpoint of differences in pedestrian and vehicle flow priorities. A nondominated sorting genetic algorithm II (NSGA II) has been developed to solve the model capably. The findings of the case study show that the model will help traffic practitioners, researchers, scientists, and administration locate and signalize properly one- or two-stage midblock pedestrians within the principal road sections.

Traffic signal timing control is a useful way for agencies to manage urban traffic without any significant infrastructure investment. Generally, the signal timings minimize the total control vehicle stoppages within a traffic juncture. The measure is quite important if the traffic juncture stands alone or if the intersection is either isolated or low-density. Nevertheless, in effect, numerous probable purposes could be included in signal timing design, namely, total passenger stoppage; pedestrian stoppages; stoppage disparity as for the competing traffic, etc. The purposes are not likely to be equal in signal timing plans; moreover, they may conflict with each other. This study proposes application of an innovative multi-objective optimization (MOO); visualization technique (i.e. the mosaic plot) to measure and establish significant compromises between the competing objectives. The set of Pareto optimal solutions, provided by MOO algorithms, may help achieve this goal. Methods are also available to define and eliminate potentially unnecessary or preventable objectives with no significant tradeoffs with others to facilitate the problem. Since MOO procedures are required if more than one objective is still available and MOO algorithms provide several hypotheses in place of a solitary final decision, two methods are proposed to order the set of Pareto optimal solutions based on their relationship with the competing objectives for a final recommendation. The methods rely on transformation of the objectives into nondimensional numbers based on the optimum for every particular objective, making it possible to compare and weigh each of them. In addition, the methods can be demonstrated with the help of a simple numerical pattern of an unimpregnated traffic juncture where each objective is obtained analytically. However, they can be easily applied to solve other signal timing problems where objectives are achieved by means of simulation to help identify the signal timing schedule providing the soundest tradeoff between the competing objectives [19].

The analysis carried out makes it possible to conclude that:

- introduction of traffic signalization within crossings is a positive factor for traffic safety;
- prolonged restrictive signals in the context of nondense traffic flow cause pedestrians to violate road laws;
- while determining the duration of a traffic light cycle, the Webster method cannot consider passenger capacity of vehicles, pedestrian density, and load of the vehicles;
- the necessity of each cycle to involve a pedestrian phase of a fixed duration results in long traffic delays, reducing the energy efficiency of public transport significantly and its environmental friendliness; and
- delay durations of pedestrians and passengers within controlled crossings are the optimization criteria of controlling modes in the context of several innovative approaches aimed at the determination of the controlling mode parameters.

### 3. FORMULATION OF THE STUDY OBJECTIVE

The objective of this study is to improve traffic efficiency within uncontrolled crossings through optimization of traffic phase duration. The following problems have been formulated for this purpose:

- to determine the optimization criterion that will result in minimum delays of each traffic member where the criterion is substantiated and the objective function is developed;
- to improve available techniques for traffic phase calculation within controlled crossing while considering the traffic density of pedestrian and passengers;
- to develop and test the technique of traffic control within crossings in the context of dense passenger flows; and
- to compare indices of the functioning efficiency of a system to control crossings while applying the developed approach and in the context of the traditional one.

#### 4. STATEMENT OF THE BASIC MATERIAL. DETERMINATION OF OPTIMIZATION CRITERION, AND THE OBJECTIVE FUNCTION

Since traffic light object functioning involves successive permission to move from conflict-controlling directions, the overall delay of all road users, passing through a crossing, is selected as an optimization criterion. Pedestrians, drivers, and vehicle passengers are involved; thus, the minimum overall delay is proposed to be the optimality criterion

$$Z = T_p + T_{pas} \rightarrow \min, \quad (3)$$

where  $T_p$  is an overall pedestrian delay, s/hour and

$T_{pas}$  is the overall delay of passengers of vehicles, s/hour.

Hereinafter, the passenger capacity of vehicles is determined by consideration of the person driving the vehicle.

Paper [2] has already established the idea of both passenger and pedestrian delays; however, a simplified formula is developed, ignoring the probability of pedestrians going onto a roadway during an enabling signal. In this context, delays of passengers and pedestrians evened against each other rather than minimized. The proposed technique proposes the following formula [20, 21] to calculate the average delay of a pedestrian  $d_p$  (s) if control is heavy:

$$d_p = \frac{0.5(T_c - t_{OT}^p)^2}{T_c}. \quad (4)$$

The overall hourly pedestrian delay is

$$T_p = N_p \cdot d_p, \quad (5)$$

where  $N_p$  is the pedestrian flow, ped./hour.

Within a crossing, the controlling cycle consists of a traffic phase and a pedestrian phase [21]:

$$T_c = t_{OT}^t + t_{PI}^t + t_{OT}^p + t_{PI}^p. \quad (6)$$

where  $t_{PI}^t$ ,  $t_{PI}^p$  are the durations of transition intervals in the transport and pedestrian phases, s.

The durations of transient intervals depend on a crossing geometry and the velocities of vehicles and pedestrians; thus, they may be considered constant for the crossing. The basic period of the pedestrian phase may be determined either using formula (7) [22] or calculated while modeling [9] or corrected by the consideration of the number of groups of pedestrians waiting for an enabling signal. Consider variant one:

$$t_{ped} = t_{PI}^p + t_{OT}^p = \frac{B}{V_p} + 5, \quad (7)$$

where  $t_{ped}$  is the minimum duration of a pedestrian phase, s;

$B$  is the length of a crossing, m; and

$V_p$  is the pace of walking, m/s.

Hence, a parameter of the basic period of a traffic phase remains variable within the cycle structure; thus, it is proposed to optimize the parameter.

[2] has developed a formula to determine the delay of all passengers.

After (4)-(6) are inserted into (3) and passenger delays are considered, we obtain

$$Z(t_{OT}^i) = N_p \frac{0,5(t_{OT}^i + t_{PI}^i + t_{PI}^p)^2}{t_{OT}^i + t_{PI}^i + t_{PI}^p + t_{OT}^p} + \sum_{i=1}^l \left( \frac{\alpha^i T_i}{k_{pr}^i} P_i k_{pm}^i \right) \rightarrow \min, \quad (8)$$

where  $P_i$  is the passenger capacity of the  $i^{th}$  type vehicle;

$\alpha^i$  is a share of  $i^{th}$  type vehicles within traffic flow;

$T_i$  is the overall delay of vehicles, s/hour;

$k_{pm}^i$  is the ratio of the passenger capacity use for the vehicle type;

$k_{pr}^i$  is the ratio of the vehicle type convergence to a passenger car; and

$l$  is the overall number of vehicle types.

Hourly delay of a vehicle is

$$T_i = N_i \cdot t_{tr}, \quad (9)$$

where  $N_i$  is the traffic density, units/h and

$t_{tr}$  is the average delay of deceleration, s.

Webster method is applied to determine  $t_{tr}$  value. [2] has reported parameter substitution and algebraic transformations.

Performing substitution in formula (8):

$$K = \sum_{i=1}^l \left( \frac{\alpha^i}{k_{np}^i} P_i k_{pm}^i \right). \quad (10)$$

After (9) and the  $t_{tr}$  value are inserted into (8), taking into consideration the (10) substitution, we obtain the expression to identify a period of overall traffic delays:

$$Z(t_{OT}^i) = \frac{0,5N_p (t_{OT}^i + t_{PI}^i + t_{PI}^p)^2}{t_{OT}^i + t_{PI}^i + t_{OT}^p + t_{PI}^p} + 0,9N_i K \cdot \left( \frac{\left( 1 - \frac{t_{OT}^i + 4}{t_{OT}^i + t_{PI}^i + t_{OT}^p + t_{PI}^p} \right)^2}{2(1-y)} \cdot (t_{OT}^i + t_{PI}^i + t_{OT}^p + t_{PI}^p) + \frac{1}{N_i} \cdot \frac{(y \cdot (t_{OT}^i + t_{PI}^i + t_{OT}^p + t_{PI}^p))^2}{2 \left( 1 - \frac{y \cdot (t_{OT}^i + t_{PI}^i + t_{OT}^p + t_{PI}^p)}{t_{OT}^i + 4} \right) (t_{OT}^i + 4)^2} \right) \rightarrow \min. \quad (11)$$

Using formula (11), we formulate the equation:

$$\frac{N_p (t_{OT}^i + t_{PI}^i + t_{PI}^p)}{t_{OT}^p + t_{OT}^i + t_{PI}^i + t_{PI}^p} - \frac{0,5N_p (t_{OT}^i + t_{PI}^i + t_{PI}^p)^2}{(t_{OT}^p + t_{OT}^i + t_{PI}^i + t_{PI}^p)^2} + \frac{y^2 (t_{OT}^p + t_{OT}^i + t_{PI}^i + t_{PI}^p)^2}{2N_i (t_{OT}^i + 4)^2 (t_{OT}^p + t_{PI}^i + t_{PI}^p - 4)} - \frac{y^2 (t_{OT}^p + t_{OT}^i + t_{PI}^i + t_{PI}^p)}{N_i (t_{OT}^i + 4) (t_{OT}^p + t_{PI}^i + t_{PI}^p - 4)} + \frac{0,45N_i K (t_{OT}^p + t_{PI}^i + t_{PI}^p - 4)^2}{(2y - 2) (t_{OT}^p + t_{OT}^i + t_{PI}^i + t_{PI}^p)^2} = 0. \quad (12)$$

To find extremums, we solve equation (12) relative to  $t_{OT}^t$  and select a value, corresponding to  $Z(t_{OT}^t)$  minimum, among its positive roots.

### 5. ANALYSIS OF SENSITIVITY OF A DURATION FUNCTION OF THE BASIC PERIOD OF A TRAFFIC PHASE

It is necessary to analyze sensitiveness of function (12) concerning its parametrization to evaluate the technique. To do that, determine the limits of values of the parameters, being a part of it (Table 1). Boundary values of the duration periods have been determined using [9, 22]. Other parameters were identified with the help of observations within fifty controlled crossings in the city of Zaporizhzhia (Ukraine).

Sensitivity is analyzed with the help of a numerical experiment. Calculate the optimum value  $t_{OT}^t$  corresponding to  $Z_{min}$ . In this context, one of the parameters varies, obtaining the minimum value, the average value, and the maximum value; all other values are registered at the level of the average ones.

Figs. 1 and 2 show the results of the sensitivity analysis.

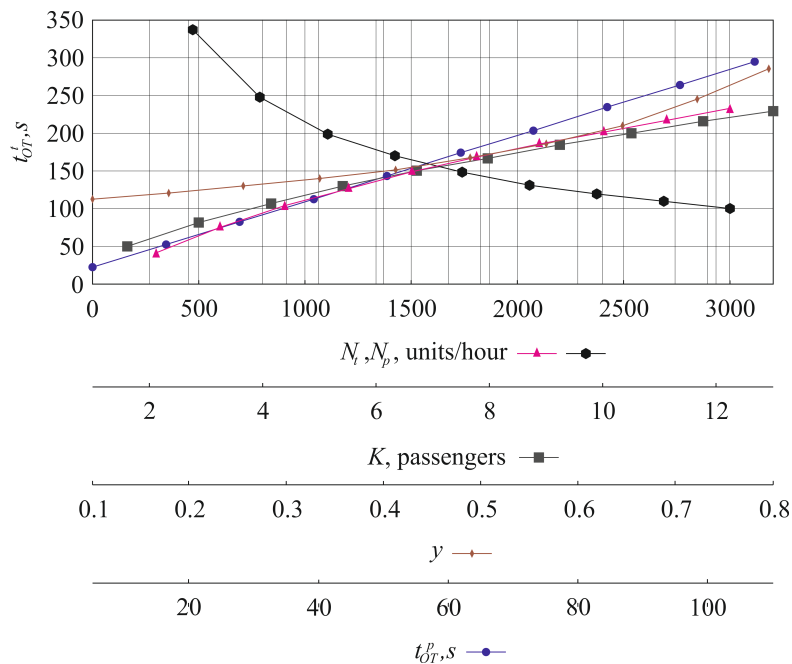


Fig. 1. Sensitivity analysis (parameters that effect considerably)

### 6. ANALYSIS OF THE EFFICIENCY OF THE PROPOSED TECHNIQUE

To ensure the efficiency of the proposed technique, durations of overall delays of road users with similar output data have been calculated; the results were then compared using the Webster method. The basic periods of a traffic phase were determined using two approaches: by solving equation (12) and by formula (2). In terms of the constant value of a saturation flow, the parameters varied within the ranges listed in Table 1.

As has already been determined, transient intervals effect  $t_{OT}^t$  insignificantly. The  $K$  parameter characterizes passenger capacity and vehicle load; thus, it is more resistant to fluctuations compared with other parameters. Taking into consideration this fact, durations of transient intervals and  $K$  value are registered in terms of average values of their ranges from Table 1.

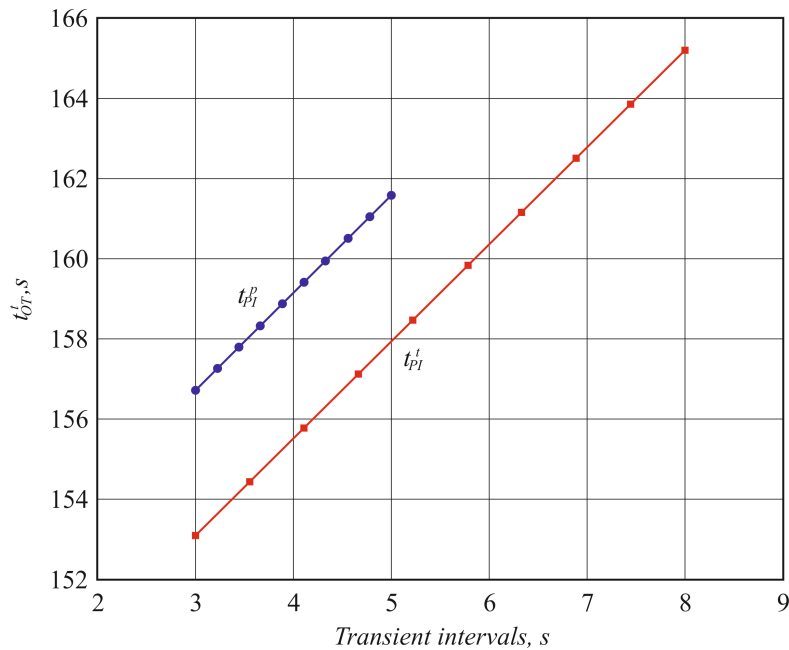


Fig. 2. Sensitivity analysis (parameters with a minor effect)

Table 1

Limits of the equation parameter values

Parameter	Value limits
Basic period of a pedestrian phase $t_{OT}^t, s$	[5..107]
Transient interval of a pedestrian phase $t_{PI}^p, s$	[3..5]
Transient interval of a traffic phase $t_{PI}^t, s$	[3..8]
Traffic intensity $N_t$ , units/hour	[300..3000]
Pedestrian intensity $N_p$ , pedestrians/hour	[150..3000]
Reduction coefficient, passengers	[1.6..13]
Phase coefficient $\gamma$	[0.1..0.8]

The  $\Delta$  value is the relative difference between the obtained durations of delays of road users determined according to formula (11) and expressed as a percentage:

$$\Delta = \frac{Z_l - Z}{Z_l} \cdot 100\%, \tag{13}$$

where  $Z_l$  is the delay of all road users determined on the basis of the basic period duration calculated using the Webster method, s/hour.

Table 2 presents the results of the calculations.

Fig. 3 shows a graph in which  $\Delta$  values were calculated while enumerating possible pairs of  $N_t$  and  $N_p$  values.

The graph shows that compared with the Webster method [23, 24], the proposed technique helps reduce delays of road users down to 35% (they are 15 to 20% in the context of ordinary conditions). This result is on a par with other current studies, in particular with [8, 25].

## 7. CONCLUSIONS

Both efficiency and environmental friendliness of road vehicles during operation have been improved through optimization of traffic phase duration within controlled crossings. An innovative optimization criterion, resulting in minimum delays for all road users during their wait for an enabling

signal, has been selected. The target function has been identified and an equation to calculate the basic period of the traffic phase has been obtained. Compared with the Webster method, the developed method and methodology reduce delays for road users by 15-20% on average.

Table 2

Results of the comparison calculations

$N_p$ , pedestrians/hour	$N_i$ , units/hour	$Y$	$t_{OT}^p$ , s	$Z_i$ , $10^4$ s/hour	$Z$ , $10^4$ s/hour	$\Delta$ , %
150	3000	0.82	5	5.15	4.16	19.3
354	2807	0.77	12	10.26	8.96	12.7
557	2614	0.71	20	14.91	13.43	10.0
761	2421	0.66	27	18.90	17.38	8.1
964	2229	0.61	34	22.15	20.72	6.5
1168	2036	0.56	41	24.62	23.39	5.0
1371	1843	0.50	49	26.32	25.35	3.7
1575	1650	0.45	56	27.24	26.56	2.5
1779	1457	0.40	63	27.39	27.00	1.4
1982	1264	0.34	71	26.78	26.63	0.6
2186	1071	0.29	78	25.42	25.41	0.1
2389	879	0.24	85	23.33	23.29	0.2
2593	686	0.19	92	20.51	20.22	1.4
2796	493	0.13	100	16.99	16.11	5.2
3000	300	0.08	107	12.77	10.86	15.0

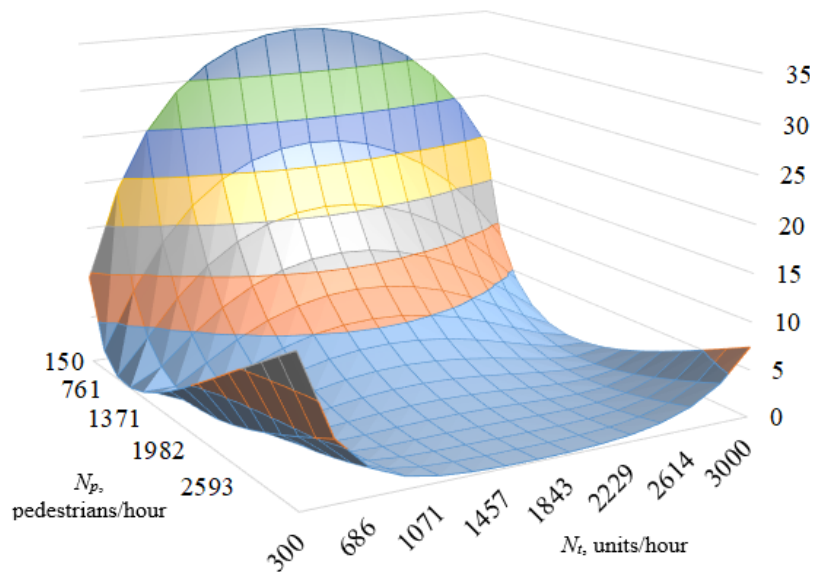


Fig. 3. Dependence of delay difference on traffic density

In the context of the technique, the reduced waiting time helps improve the efficiency of public transport characterized by relatively high passenger capacity and significant energy consumption per driven kilometer due to the specific nature of urban traffic conditions involving frequent stops. Since pedestrian delays reduce, the number of violations of controlling signals decreases as well [7].

The study of the sensitivity function of the optimum duration of the traffic phase made it possible to determine the nature of the effect of the parameters on the basic period duration. If the optimum value  $t_{OT}^t$  is beyond the specified range, then the graphical representation of the effect of the basic parameters

upon the  $t_{OT}^t$  value helps select the most effective measure to organize traffic, providing the best approach of controlling mode parameters to optimum values. Such measures include changes in the crossing width, availability of refuge islands, pedestrian flow distribution among several crossings, and changes in traffic flow composition [21, 26].

A minor effect of transient intervals on the optimum basic period of a traffic phase means that their prolongation may improve road safety, with no increase in delays for road users [27, 28].

The improved efficiency of motor transport functioning owing to reduced traffic delays within crossings will also lead to decreases expenditures in relation to freight forwarding services; in turn, this will factor into synergetic effects in the context of transport and logistics systems [29, 30].

When pedestrian density is high, they go onto a roadway in several lines; in this case, corrections of the duration of the basic period of the pedestrian phase are required. If so,  $t_{OT}^p$  is a function of pedestrian density. Consideration of time when pedestrian groups go onto a roadway result in the complication of equation (12); thus, this is a subject for further research.

## References

1. World Health Organization. *Global status report on road safety 2015*. World Health Organization, 2015.
2. Трушевський, В. & Грицай, С. & Никифоровський, Д. Мінімізація затримок учасників дорожнього руху на регульованих пішохідних переходах. *Східно-Європейський журнал передових технологій*. 2014. Vol. 5(3). P. 25-29. [In Ukrainian: Trushevskij, V. & Gricaj, S. & Nikiforovskij, D. Minimization of delays of road users on regulated crosswalks. *Eastern-European journal of enterprise technologies*].
3. Рахмангулов, А. & Ломакина, М. Выбор направления совершенствования систем светофорного регулирования транспортных потоков в городах. *Современные проблемы транспортного комплекса России*. 2017. Vol. 7. No. 1. P. 27-34. [In Russian: Rakhmangulov, A. & Lamakina, M. Selecting the direction of improving the traffic light system of urban traffic flows management. *Sovremennye problemy transportnogo kompleksa Rossii*].
4. Marisamynathan, S. & Vedagiri, P. Modeling pedestrian delay at signalized intersection crosswalks under mixed traffic condition. *Procedia-Social and Behavioral Sciences*. 2013. Vol. 104. P. 708-717. DOI: 10.1016/j.sbspro.2013.11.165.
5. Guo, R. & Lu, X. Delays for both pedestrians classified and vehicles at a signalized crosswalk. *Journal of Systems Science and Complexity*. 2016. Vol. 29. No. 1. P. 202-218.
6. Dommes, A. Red light violations by adult pedestrians and other safety-related behaviors at signalized crosswalks. *Accident Analysis & Prevention*. 2015. Vol. 80. P. 67-75.
7. Brosseau, M. The impact of waiting time and other factors on dangerous pedestrian crossings and violations at signalized intersections: A case study in Montreal. *Transportation research part F: traffic psychology and behaviour*. 2013. Vol. 21. P. 159-172. DOI: 10.1016/j.trf.2013.09.010.
8. Marisamynathan, S. & Vedagiri, P. A new approach to estimate pedestrian delay at signalized intersections. *Transport*. 2018. Vol. 33. No. 1. P. 249-259.
9. Yu, C. Optimization of vehicle and pedestrian signals at isolated intersections. *Transportation Research Part B: Methodological*. 2017. Vol. 98. P. 135-153. DOI: 10.1016/j.trb.2016.12.015.
10. Mishra, S. Evaluating the Impacts of Existing Priority and Developing a Passenger Based Transit Signal Priority. *MS Thesis*. 2016.
11. Wang, L. & Zhou, Y. Optimization of Intersection Phase and Signal Timing. *Journal of Xi'an Technological University*. 2012. Vol. 12. P. 16.
12. Ren-Yong, G. & Xi, G. Interactions between intersecting pedestrian and vehicle flows on roads. *Chinese Physics Letters*. 2011. Vol. 28(11). P. 118903.
13. Pan, Q. & Zhu, Y. Delay analysis of the vehicle at signalized intersection. *Journal of Systems Science and Mathematical Sciences*. 2009. Vol. 29(6). P. 728-734.

14. Chen, P. & Zheng, F. & Lu, G. & Wang, Y. Comparison of variability of individual vehicle delay and average control delay at signalized intersections. *Transportation Research Record*. 2016. Vol. 2553(1). P. 128-137.
15. Tao, Y. & Wei, Y. & Gao, Q. & Dong, L. Pedestrian-vehicle interference at a signalized crossing based on detailed microscopic traffic flow models. *Acta Physica Sinica*. 2019. Vol. 68(24). P. 240505.
16. Zhang, Y. & Mamun, S. & Ivan, J. & Ravishanker, N. & Haque, K. Safety effects of exclusive and concurrent signal phasing for pedestrian crossing. *Accident Analysis & Prevention*. 2015. Vol. 83. P. 26-36.
17. Forde, A. & Janice, D. Pedestrian walking speed at un-signalized midblock crosswalk and its impact on urban street segment performance. *Journal of Traffic and Transportation Engineering (English Edition)*. 2020. DOI: <https://doi.org/10.1016/j.jtte.2019.03.007>.
18. Yu, C. & Ma, W. & Yang, X. Integrated optimization of location and signal timings for midblock pedestrian crosswalk. *Journal of Advanced Transportation*. 2016. Vol. 50(4). P. 552-569.
19. Hitchcock, O. & Gayah, V. Methods to reduce dimensionality and identify candidate solutions in multi-objective signal timing problems. *Transportation Research Part C: Emerging Technologies*. 2018. Vol. 96. P. 398-414.
20. Ma, W. & Liao, D. & Liu, Y. & Lo, H. Optimization of pedestrian phase patterns and signal timings for isolated intersection. *Transportation Research Part C: Emerging Technologies*. 2015. Vol. 58. P. 502-514.
21. Yang, Z. & Benekohal R. Use of genetic algorithm for phase optimization at intersections with minimization of vehicle and pedestrian delays. *Transportation research record*. 2011. Vol. 2264. No. 1. P. 54-64.
22. Трушевський, В. & Грицай, С. Особливості корекції елементів циклу світлофорного регулювання з метою гарантування безпеки руху пішоходів. *Автомобілівник України*. 2014. Vol. 5. P. 20-22. [In Ukrainian: Trushevsky, V. & Gritsaj, S. Features of cell traffic light cycle correction to guarantee the pedestrians' safety. *A Scientific and Industrial Journal the Avtoshliakhovyk Ukrayiny*].
23. Zhihui, L. & Qian, C. & Yonghua, Z. & Pengfei, T. & Rui, Z. Krill herd algorithm for signal optimization of cooperative control with traffic supply and demand. *IEEE Access*. 2019. Vol. 7. P. 10776-10786.
24. Qadri, S.S.S.M. & Gökçe, M.A. & Öner, E. State-of-art review of traffic signal control methods: challenges and opportunities. *European transport research review*. 2020. Vol. 12(1). P. 1-23.
25. Tana, M.K. & Chuo, H.S.E. & Lim, K.G. & Chin, R.K.Y. & Yang, S.S. & Teo, K.T.K. A comparison study of deterministic and metaheuristic algorithms for stochastic traffic flow optimization under saturated condition. *Ictact journal on soft computing*. 2020. Vol. 10. No. 3. P. 2117-2123.
26. Gao, Y. & Qu, Z. & Jiang, J. & Song, X. & Xia, Y. Mixed traffic flow signal timing optimization method considering e-bike expansion influence. *Journal of transportation engineering. Part A: Systems*. 2021. Vol. 147(2). DOI: <https://doi.org/10.1061/JTEPBS.0000478>.
27. Iryo-Asano, M. & Alhajyaseen, W. & Nakamura, H. Analysis and modeling of pedestrian crossing behavior during the pedestrian flashing green interval. *IEEE Transactions on Intelligent Transportation Systems*. 2015. Vol. 16. No. 2. P. 958-969.
28. Turpak, S. & Taran, I. & Fomin, O. & Tretiak, O. Logistic technology to deliver raw material for metallurgical production. *Naukovyi visnyk Natsionalnoho hirnychoho universytetu*. 2018. No. 1. P. 162-169.
29. Shramenko, N. Methodology for evaluation of synergy effect in terminal cargo delivery system. *Actual Problems of Economics*. 2016. Vol. 8(182). P. 439-444.
30. Sabraliev, N. & Abzhapbarova, A. & Nugymanova, G. & Taran, I. & Zhanbirov Zh. Modern aspects of modeling of transport routes in Kazakhstan. *News of the National Academy of sciences of the Republic Kazakhstan*. 2019. Vol. 2(434). P. 62-68.